

CRANFIELD UNIVERSITY

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KNOWLEDGE MODELLING FOR THE LASER BEAM WELDING  
PROCESS IN THE AIRCRAFT INDUSTRY

SCHOOL OF APPLIED SCIENCES

MSc by Research Thesis  
Academic Year: 2010 - 2011

Supervisors: Dr. Essam Shehab and Dr. Jorn Mehnen  
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This thesis is submitted in partial fulfilment of the requirements for  
the degree of Master of Science

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## **ABSTRACT**

The Laser Beam Welding (LBW) process offers the possibility of manufacturing joints from most light metals and their combinations, as well as simplifying and integrating the fuselage structure to reduce weight and cost, which are the main concerns of the modern aircraft industry. However, there has been little published knowledge detailed on the LBW process in the aircraft industry yet, which has limited its dissemination. Hence, there is a need to capture knowledge about the LBW process in the aircraft industry for its wider and more effective usage.

This research aims to develop a knowledge model of the LBW process in the aircraft industry to improve structure design and process planning. The main objectives are to: (i) identify the methods and tools for knowledge capture and representation; (ii) identify the considerations of structure design and process planning for LBW; (iii) capture the knowledge about structure design and process planning in the form of rules and recommendations, and represent them with Unified Modelling Language (UML); (iv) apply the captured knowledge to a fuselage panel of a commercial aircraft; (v) validate the developed model through case study and expert judgement. These objectives were achieved through the adoption of a four-phase research methodology: understanding the context, data collection and analysis, knowledge model development and validation.

The captured knowledge in the form of rules and recommendations has developed an understanding of the LBW process in the aircraft industry and improved the structure design and process planning. The handbook developed based on skin-stringer connection guides designers and engineers directly to developing Laser Beam Welded fuselage panels. This research project has contributed to a wider and more effective use of LBW in the aircraft industry. The procedure of knowledge modelling which includes knowledge identification, capturing and representation, as well as the methods and tools adopted for these stages can be applied to other process knowledge modelling.

**Keywords:** Laser Beam Welding, Aircraft industry, structure design, process planning, Knowledge modelling

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## **ACKNOWLEDGEMENTS**

I appreciate my supervisors Dr. Essam Shehab and Dr. Jorn Mehnen greatly for their supervision and support during this work. Without their advice and suggestions, this work would have suffered greatly.

I also want to express my gratitude to Dr. Ahmed Al-Ashaab and Mr Suder Wojciech of Cranfield University as well as Dr. Zhan Xiaohong, Dr. Liu Hongbing and Dr. Sun Zhonggang in COMAC for their help with the research topic. Their advice, cooperation and comments have advanced this research greatly.

Furthermore, I would like to thank Wang Yang, Li Hao, Yang Zhibing and all the interviewees who have completed the questionnaire and taken part in the semi-structured interviews. They have provided much useful information and contributed to this research project.

I would also like to thank the China Scholarship Council and COMAC for sponsoring my studies, Cranfield University for the study resources and Dr Al Savvaris, Mrs Angela Miller as well as my colleagues and friends both in Cranfield University and COMAC for their attention and support during this year.

My thanks also must extend to my family, parents and wife, for their understanding and support during this year.

Thank you all.

Sun Xiaofeng

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## LIST OF ABBREVIATIONS

AA	Aluminium Association
Al-Li	Aluminium-Lithium
Al-Mg-Sc	Aluminium-Magnesium-Scandium
AWS	American Welding Society
ALCAN	Aluminium Company of Canada
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CE	Concurrent Engineering
COMAC	Commercial Aircraft Corporation of China
CU	Cranfield University
DFMA	Design for Manufacturing and Assembling
FEA	Finite Element Analysis
GMA	Gas Metal Arc welding
HAZ	Heat Affected Zone
IDEF0	Integration Definition for Function Modelling
KM	Knowledge Management
KR	Knowledge Representation
KLC	Knowledge Life Cycle
LBW	Laser Beam Welding
MS	Material Specification
Nd:YAG	Neodymium-doped Yttrium Aluminium Garnet
PPR	Product, Process and Resource
PPRR	Process Planning Rules and Recommendations
PS	Process Specification
QC	Quality Control
RRS	Rules and Recommendations Set
SDRR	Structure Design Rules and Recommendations
UML	Unified Modelling Language

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# 1 Introduction

## 1.1 Background

With the progress of globalization and development of technology, most aircraft manufacturing companies are facing fierce competition while operating in the changing market of today. During aircraft development, weight reduction and cost saving are always among the main concerns. The strategy to address these concerns can be characterised by the development of new materials, advanced processes and new integral design principles.

Although the application of composites has been increasing dramatically recently (Ma, 2010), reaching 50% and 53% of the structure mass for B787 and A350 respectively, as shown in Table 1-1, light metals, such as Aluminium and Titanium, still account for over 30% of the structure mass. The development of the 3<sup>rd</sup> generation of Al-Li (Aluminium-Lithium) alloys and Al-Mg-Sc (Aluminium-Magnesium-Scandium) alloys illustrates that metal technology in the aircraft industry will keep developing (Lassince et al., 2006; ALCOA, 2011). Thus, a study of technologies and manufacturing processes which focuses on these light metals still has great potential. The Laser Beam Welding (LBW) process has been developing rapidly in recent decades as it is possible to manufacture joints of most light metals and their combinations (Schubert et al., 2001). Simultaneously, utilization of the LBW provides the possibility to integrate and simplify the structure, and reduce the weight and cost (Walz, 2002) to meet the main concerns of the aircraft industry today.

Table 1-1 Material composition of commercial aircraft (Grandine, 2010; Vogelaar, 2009; Campbell, 2006)

	Composite	Aluminium	Titanium	Steel	Other
<b>A320</b>	15%	65%	6%	11%	3%
<b>A380</b>	25%	61%	10%(Titanium & Steel)		4%
<b>B777</b>	11%	70%	7%	11%	1%
<b>A350 XWB</b>	53%	19%	14%	6%	8%
<b>B787</b>	50%	20%	15%	10%	5%

The first production fuselage shell using LBW was approved in 2001 for the A318, and more than 1200 shells for the A318, A340 and A380 have been produced from 2001 to 2010 (Rendigs and Knowler, 2010). However, Airbus is the only company to have successfully applied LBW to aircraft fuselage panels, although many other companies have shown great interest. Commercial security reasons are responsible for the knowledge without wide dissemination.

Knowledge modelling is a key procedure within knowledge management (KM), which is necessary for the company to innovate on products and processes, and reducing cost. Most of the cost is determined at the design and planning stages during product development. The more problems prevented in these two stages through careful design and process planning, the fewer problems will occur later which are expensive to change. Thus, it is necessary to reduce the “knowledge gap” between design and manufacture, as illustrated in Figure 1-1 (Swift and Booker, 2003; Bernard and Tichkiewitch, 2008). Knowledge modelling plays an important role in this approach.

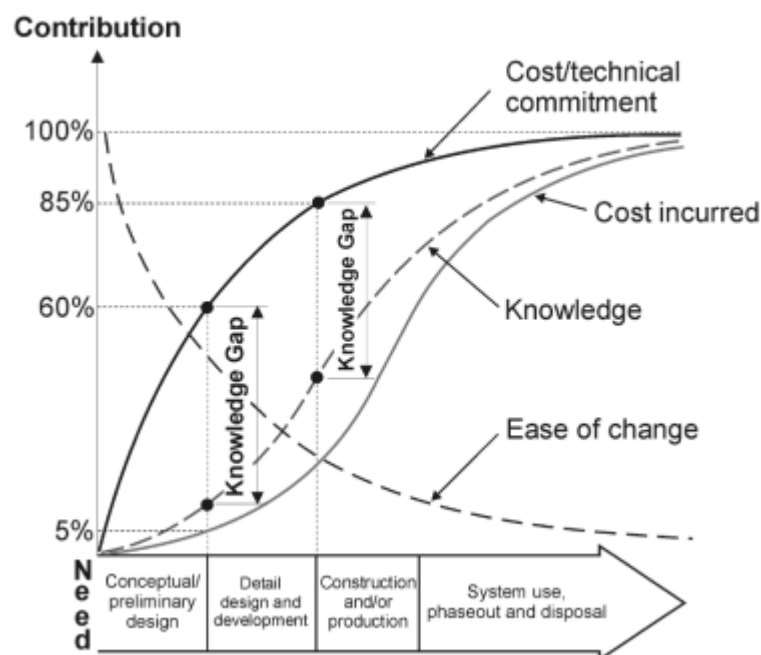


Figure 1-1 Cost during product development (Swift and Booker, 2003)

Airbus has illustrated the potential of the LBW process in the modern aircraft industry, but as a commercially confidential issue, the knowledge about this process in the aircraft industry has not been spread yet. Any company wanting to apply this technology to real production, such as fuselage panel fabrication, should first capture knowledge about this process.

## **1.2 Research Motivation**

Brenner, a team leader of the LBW project cooperating with Airbus for aircraft fuselage panel development, states that advanced structure design and process planning are preconditions for a wider and more effective use of the LBW process (Brenner et al., 2008). However, structure design and process planning are usually guided by rules and recommendations in the aircraft industry. Thus, it will contribute to a wider and more effective use of the LBW process if knowledge of the process in the aircraft industry is captured in the form of rules and recommendations and utilized to guide structure design and process planning. However, such rules and recommendations for the LBW process are still lacking in the aircraft industry today.

## **1.3 Problem Statement**

Although LBW is an accurate and high speed process and brings advantages of significant weight and cost reduction to the aircraft industry, it is difficult to achieve because there are many variables which make this process complex, such as the joint type and structure, the process type and parameters as well as the fixtures. All these aspects have a great influence on the achievement of those advantages.

The selection of joint type, structure and material determines the potential weight reduction and possibility of utilizing LBW, while the selection of process and parameters as well as the design of fixtures decide how good the welding results will be, including the as-welded geometry and possible defects. An improper definition of these variables will bring limitations to this process or even cause problems. For example, if the stringer is designed as a “Z” type as illustrated in Figure 1-2, it will not bring a significant weight reduction compared with the traditional riveting process. Furthermore, close fitting and well clamping as well as exact positioning are required for LBW, otherwise the accurate beam/joint alignment can not be achieved and the welding may not be finished properly. It is important to make the proper choice of these variables, which is also difficult to do.

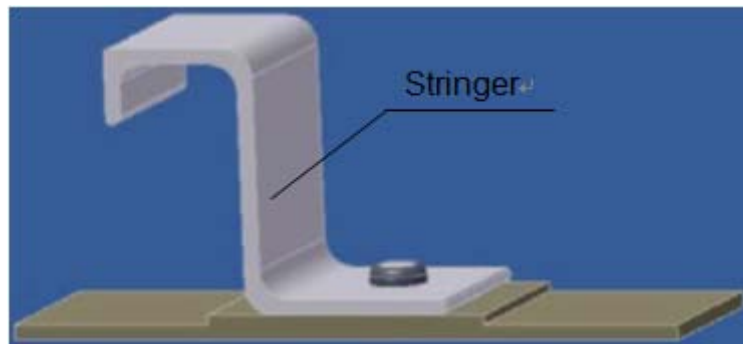


Figure 1-2 Typical structure of “Z” type stringer (Dittrich et al., 2011)

## 1.4 Project Scope

The scope of this project includes knowledge identification, capturing and representation of the LBW process in the aircraft industry, covering fuselage panel structure design and process planning which will influence the LBW process capabilities directly. This is achieved through:

- A comprehensive literature review, questionnaire and a series of interviews to identify the key considerations of fuselage panel structure design and process planning for LBW.
- Capturing knowledge about structure design and process planning for LBW in the form of rules and recommendations.
- Representing the knowledge with Unified Modelling Language (UML).
- Validation of the captured knowledge.

The scope of this project does not include best practices outside the aircraft industry, and any other materials except aluminium alloys. Other stages of the Knowledge Life Cycle (KLC), such as sharing of the knowledge and knowledge-based engineering are deemed to be outside the scope of this research.

## 1.5 The Collaboration Company

The Commercial Aircraft Corporation of China (COMAC) is a State-owned company in China, adopting a "Main manufacturers - Suppliers" model, which means a wide cooperation with aircraft manufacturers or suppliers all over the world. Its main functions include aircraft design, manufacture, marketing and acquisition of certification. It is engaged in the research and manufacture of civil



aircraft which are safe, economical, comfortable and environmentally friendly as well as the development of a world-class reputation in the aviation industry. Thus, it is always interested in those techniques and processes which are capable of increasing aircraft performance or reducing weight and cost.

COMAC has been studying the LBW process in recent years and intends to apply this process to real production, because it is thought to be a trend of metal fuselage development and is capable of bringing significant weight and cost reduction to fuselage panels. The company has finished a number of experiments with specimens of joint structure to test and verify this process, and now has massed much data and experience. However, it is still far away from applying LBW to real production because there is still a lack of guidelines for structure design and process planning as well as Process Specification. The knowledge modelling of this process is a challenge for its implementation. Thus, COMAC has collaborated with this research for knowledge modelling of the LBW process in the aircraft industry.

## **1.6 Aim and Objectives**

The aim of this research project is to develop a knowledge model for the Laser Beam Welding (LBW) process in the aircraft industry to improve structure design and process planning.

The objectives of this research are to:

1. Identify the methods and tools for knowledge modelling;
2. Identify the considerations of structure design and process planning for LBW;
3. Capture the knowledge about structure design and process planning for LBW in the form of rules and recommendations, and represent them with UML;
4. Apply the captured knowledge to a fuselage panel of a commercial aircraft;
5. Validate the developed model through case study and expert opinion.

## **1.7 Thesis Structure**

The thesis comprises eight chapters as illustrated in Figure 1-3. The first chapter provides an overall introduction to the research topic. Chapter 2 presents a

comprehensive literature review which is conducted to gain foundational knowledge. Chapter 3 defines the adopted research methodology. Chapter 4 illustrates the identified methods and tools for knowledge capture and representation. Chapter 5 presents the collected data and information, as well as the results of analysis. Chapter 6 introduces the knowledge modelling procedure, including identifying the considerations, capturing the knowledge as rules and commendations, and representing them with UML. Chapter 7 introduces the validation process and results of expert judgement, so as to validate the captured knowledge. The last chapter discusses the literature review, research methodology, achievement of objectives and contributions, and a conclusion is provided finally.

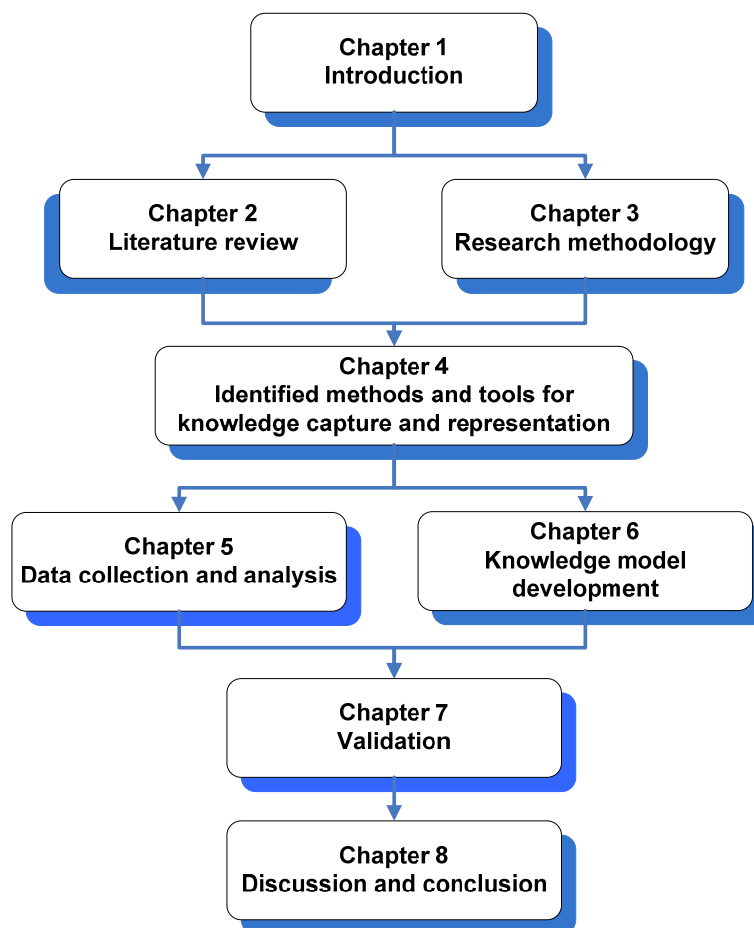


Figure 1-3 Thesis structure

## 1.8 Summary

This chapter has given a general introduction to the research project detailed within this thesis. Brief background information of the LBW process and

knowledge modelling is described firstly, followed by the research motivation, problem statement, project scope, the collaboration company as well as the aim and objectives of this research. The thesis structure is illustrated in Figure 1-3.

## 2 Literature Review

### 2.1 Introduction

A comprehensive literature review has been conducted in this chapter to obtain fundamental knowledge for this project. The whole chapter is divided into seven sections as illustrated in Figure 2-1. Section 2.1 gives a brief introduction. Section 2.2, 2.3 and 2.4 present the literature about knowledge modelling, LBW and aircraft industry product development, respectively. Section 2.5 introduces some existing research related to this project, and then some research gaps are identified in section 2.6. Finally, a summary to this chapter is given in section 2.7.

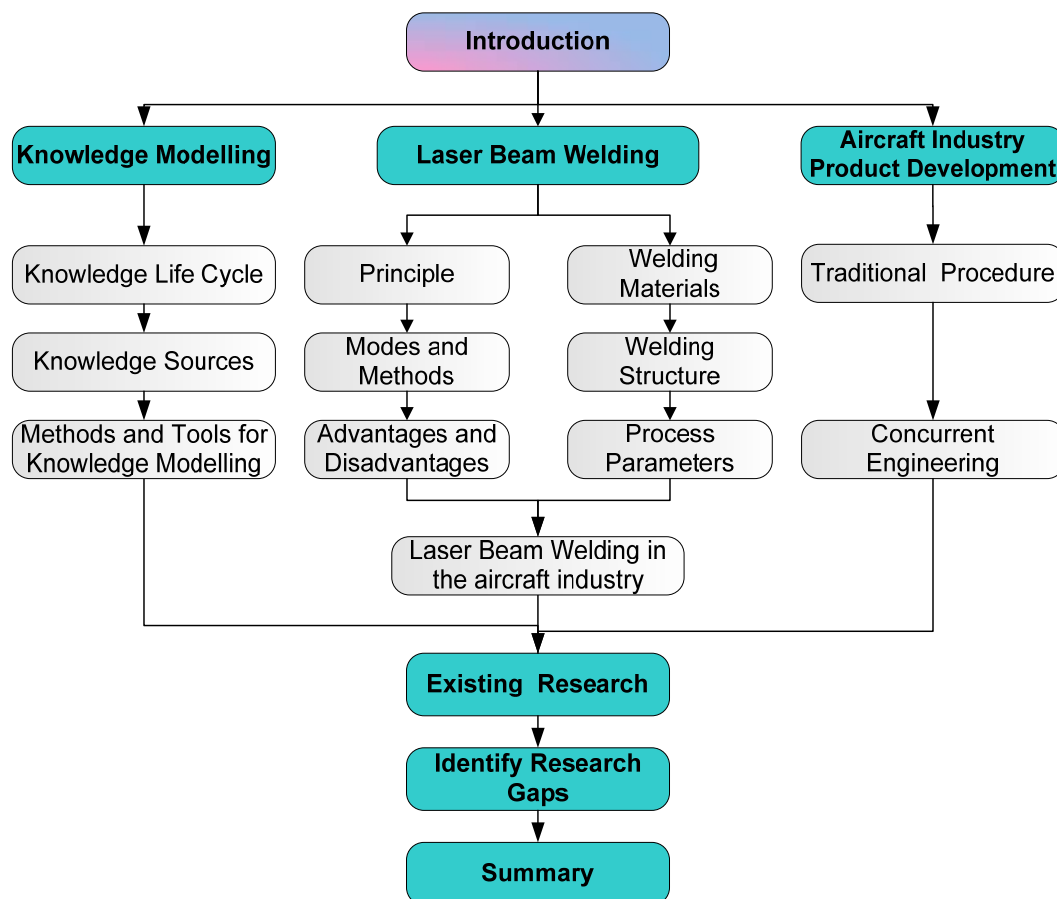


Figure 2-1 Literature Review Structure

### 2.2 Knowledge modelling

Knowledge modelling is the process to create knowledge, which is a key procedure within Knowledge Management (KM). It contributes to a developed understanding of the knowledge, including knowledge source, the inputs and

outputs, the flow of knowledge and other variables (Davenport and Prusak 2000). Knowledge modelling is capable of breaking the objects down into more manageable parts which are easy to understand and manipulate, so as to capture the essential features of them (Abdullah et al., 2002).

### 2.2.1 Knowledge Life Cycle

To understand knowledge modelling, the Knowledge Life Cycle (KLC) should be reviewed first because KM is about managing KLCs and their processes. The literature shows that KLC studies are receiving increasing attention as the concept that KM is about managing KLCs and their processes is becoming widely accepted (Firestone, 2002).

KLC means the whole procedure of knowledge, including creating, utilization and maintaining. Three KLCs from MOKA (2001), Rodriguez and Al-Ashaab (2007) and Maksimovic et al. (2011), were reviewed in this project. Their different decompositions are listed in Table 2-1. Two issues have been addressed within these three KLCs. 1). Knowledge identification, capture and representation/formalize are defined in each of the three KLCs; 2). Decompositions of KLCs are developing and becoming much clearer. These issues will contribute to the selection of KLC for this project in chapter 4.

Table 2-1 Decomposition of different Knowledge Life Cycles

Sources	MOKA, 2001	Rodriguez and Al-Ashaab, 2007	Maksimovic et al., 2011
Decompositions	Identify	Identify	Identification
	Justify		
	Capture	Capture/ Acquire and standardize	Domain knowledge capture
	Formalize	Represent	Representation
			Sharing
	Package	Implementation	KBE
	Activate	Use	Use and knowledge provision
		Create	Dynamic knowledge capture
		Maintain and upgrade	

Overall, the definition of KLCs is developing, and the decompositions of KLCs are becoming more and more particular. A consensus seemed to be reached that knowledge identification, capture and representation are the main approaches of KLC, which can be chosen in this project for knowledge modelling for the LBW process in the aircraft industry.

## 2.2.2 Sources of Knowledge

It is commonly accepted that knowledge can be divided into explicit and tacit knowledge in general. Explicit knowledge is formal knowledge that can be obtained from norms, books, documents, technical manuscripts, drawings, databases and websites, whilst tacit knowledge, in the form of experience, skills, insights and hunches, is stored in experts' minds and is difficult to discover and extract (Swartout and Gil, 1996; Awad and Ghaziri, 2007). However, engineers could gain "know-how" or tacit knowledge from expertise, practices and learning from formal sources of knowledge, such as literature and trainings. Figure 2-2 illustrates some different knowledge sources classified by knowledge type. After training, studying and practising about explicit knowledge, some tacit knowledge could be gained in the form of experience, insight and stored in the expert' mind. On the other hand, partially tacit knowledge, such as experience and skills, could be captured and documented and therefore transferred to explicit knowledge (Tamarit, 2010).

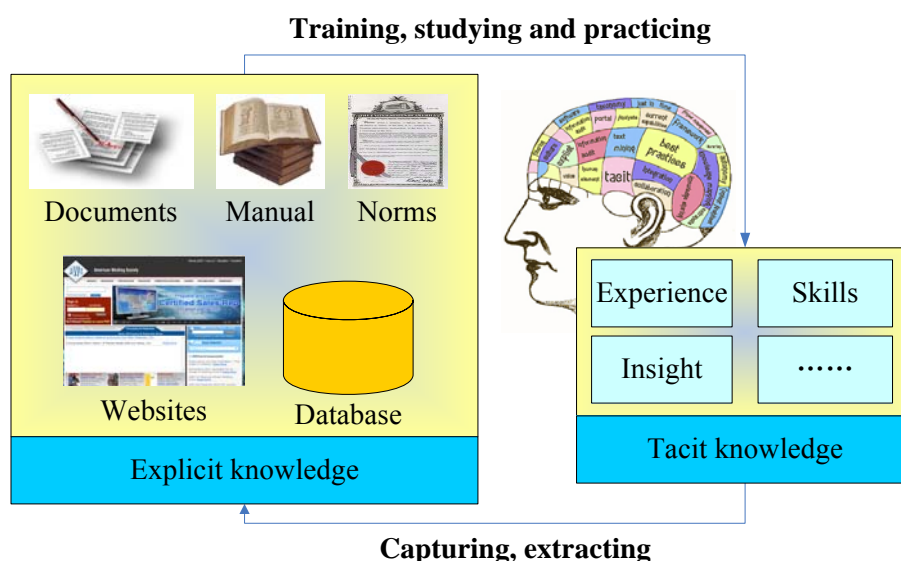


Figure 2-2 Knowledge sources classified by knowledge type (Tamarit, 2010)

The sources mentioned in the foregoing paragraph include not only technical lessons learned and best practices, but also broader perspectives such as programme or project management, critical processes and functional support activities (Joseph and Dyer, 2010). Figure 2-3 illustrates a three axes (H-V-PP) system to locate where knowledge can be captured during product design and development. The H-axis means different stages within the product development, the V-axis represents concurrent engineering between different departments and the PP-axis stands for historical, previous projects (Maksimovic et al., 2011). This model is especially suitable for a company with a long history of product development experience and complex organizations, and is applicable to COMAC.

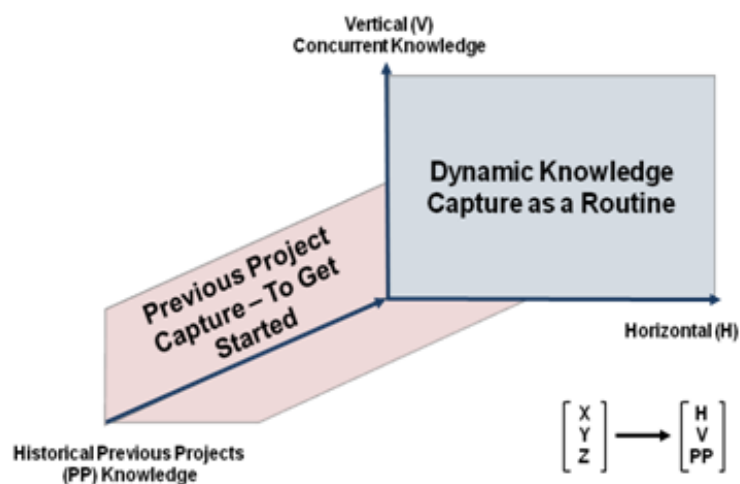


Figure 2-3 Knowledge capture during product design and development  
(Maksimovic et al., 2011)

For material processing, Rentzsch et al. (2005) recommend knowledge mapping to locate knowledge about the impact of process stages to the product attributions; this is simplified and illustrated in Figure 2-4. With this method, the impact of every process stage on every product attribute can be captured and visualised systematically. It is obviously a wonderful method for knowledge integration and navigation as well as knowledge gap identification.

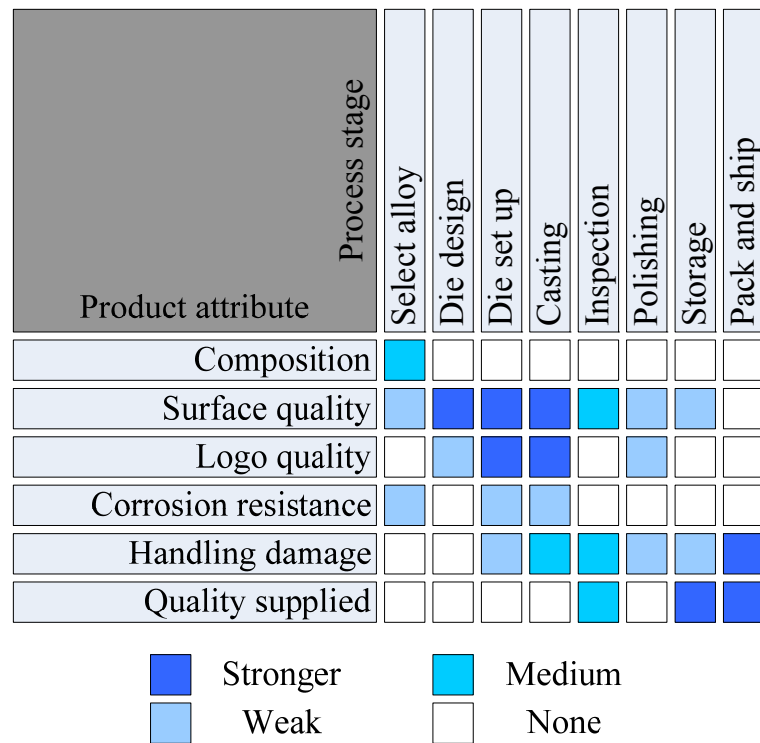


Figure 2-4 A simplified knowledge map (Rentzsch et al., 2005)

## 2.2.3 Methods and Tools for Knowledge Capture and Representation

Many methods and tools have been developed and identified for knowledge capture and representation so far, such as decision trees, mind/concept/process mapping, interviews, observation and commenting (Sun and Gang, 2006; Mohammad and Nedhal, 2010). Among these methods and tools, questionnaires and interviews are the most used for tacit knowledge capture. Some of the methods were reviewed and analysed in this section according to Awad and Ghaziri (2007) and Mohammad and Nedhal (2010).

### 1) Interview

The aim of this technique is to capture knowledge from experts or an organization and produce a record with a certain media, such as audio, video, electronic and paper media. It can be combined with workshops to establish commitment from a group of experts. Mohammad and Nedhal (2010) propose a guideline for interviewing to acquire knowledge from experts, the suggested procedure for which is illustrated in Figure 2-5. A good preparation of the interview with specific questions or focused topic is crucial for this method.



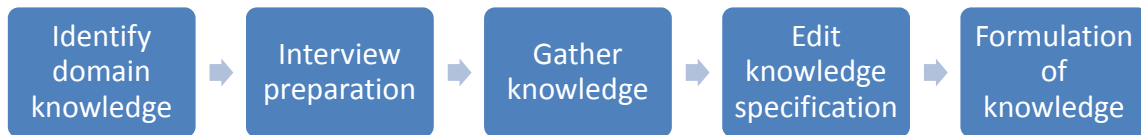


Figure 2-5 Interview processes (Mohammad and Nedhal, 2010)

There are three main types of interview, namely unstructured, semi-structured and structured, which can be applied to different situations. Unstructured interviews have no pre-defined questions or structure, while semi-structured interviews have a structured agenda with the flexibility to ask additional questions following an answer and structured interviews allow no flexibility with all questions pre-established. The questionnaire is a special kind of structured interview in that the questions can be finished by the interviewees independently. It is most used for general knowledge capture and was utilized to collect information and for validation in this project.

## **2) Concept/Mind Mapping and Semantic Network**

Concept/Mind mapping and semantic network all are graphical tools for knowledge capture and representation. They consist of nodes denoting concepts or objects and links between the nodes denoting object relations (Awad and Ghaziri, 2007). The labelled links can be used to express various forms of relations, such as is-part-of and x-contains-y. They can be utilized either for retrieving knowledge from existing explicit knowledge or capturing tacit knowledge from experts in a graphical way.

Concept mapping is used to design a complex structure, generate ideas, communicate complex ideas or diagnose misunderstanding while mind mapping is used to generate, visualize, structure, and classify ideas, and as an aid to studying and organizing information, solving problems and making decisions (Beel et al., 2009). The structure of a mind map is a similar radial with only one central key word comparing with the concept map. The semantic network is a graphic tool used to encode relationships and capture knowledge. It is a collection of nodes linked together to form a net, which is similar to concept mapping. It is also an efficient method to represent knowledge, which has been utilized by many researchers. For example, Hao et al. (2005) has used semantic

network to represent knowledge about machining process which makes process planning much easier. Yang et al. (2009) has presented a method for product knowledge representation with semantic net which makes it much clearer.

### **3) Rules**

Rules are often utilized to capture and represent knowledge as they can be easily recognized by computers and are convenient to be applied to knowledge system. For example, some of the rule-based approaches are made up of IF-THEN rules. The IF-part contains one or more conditions and is called the antecedent, whilst the THEN-part is the consequent (Chen et al., 2011). Application of rules in welding can be found from Tamarit (2010) and Lamacchia (2010). Tamarit has used IF-THEN rules to check the input as a condition for joining and welding processes while Lamacchia has used IF-THEN rules to check whether the design is respecting the design constraints. Simultaneously, Lamacchia (2010) has used recommendation rules to suggest suitable tool design solutions and present the expected effects for joining tool design, which is general but efficient for tool design.

### **4) UML**

UML is an integration of those graphical methods, such as concept/mind map and semantic net, which is now a standard language for object modelling. There are several different types of UML models, such as class diagram and activity diagram, to visualize the knowledge from different points of view (Abdullah et al., 2002). The activity diagrams are capable of describing activities and actions occurring in a system (Noran, 2000). In process modelling, activity diagrams may be used to model manufacturing processes (defined as a flow or sequence of activities). This modelling can be achieved via object or control flow. Because the knowledge is represented graphically, it is easy to understand. This is the main reason that UML is popular for knowledge representation today.

## **2.2.4 Process Modelling**

Process knowledge is related to engineering, maintenance and operations, which is characterized by stages, actions or events, with each stage having inputs and outputs. It is often found in procedures. Much tacit knowledge is

process knowledge (Awad and Ghaziri, 2007). Thus, it is difficult to capture such knowledge. There is no universal standard for process modelling. One efficient method is called process mapping which is a workflow diagram to bring forth a clear understanding of a process. Figure 2-6 illustrates a process map for cost / time model development and validation procedure, in which all the stages as well as the sequence of these stages are made clear. A wonderful tool for process mapping is called IDEF0 which will be introduced in the next sub-section.

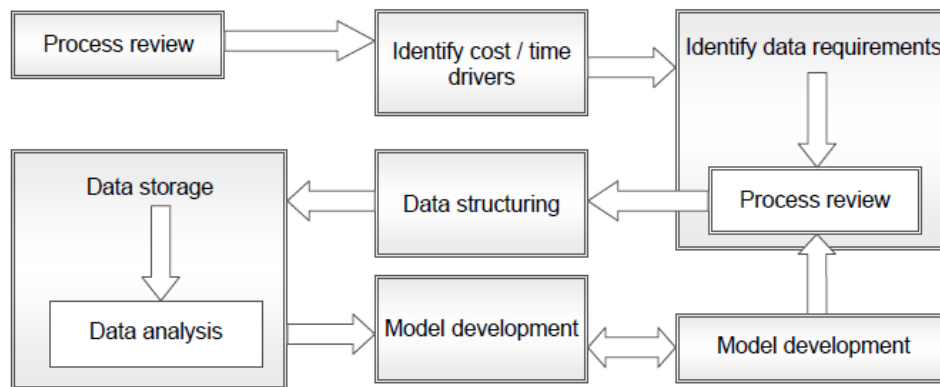


Figure 2-6 Cost /time model development process (Bush, 1994)

## 1) IDEF0

IDEF0 (Integration Definition for Function Modelling) offers a functional modelling language for the analysis, development and integration of processes (Defense Acquisition University, 2001), thus it is often used for describing manufacturing functions. A schematic diagram of IDEF0 model is illustrated in Figure 2-7, with a centre box and arrows. Each activity is described by a verb-based label placed in a box. Inputs are presented as arrows entering the box on the left side while Outputs are illustrated as arrows exiting the box on the right side. Controls are on the top and Mechanisms are on the bottom of the box, both of which are shown as entering arrows. Inputs, Controls, Outputs, and Mechanisms are all referred to as concepts. (Grover and Kettinger, 2000)

Process mapping by IDEF0 is excellent for process knowledge modelling, because the inputs, outputs, controls and mechanics of each stage of the process can be illustrated in the map clearly. Thus, almost all the considerations about the process can be identified through the IDEF0 map, which makes process knowledge capturing much easier. Whiteside (2008) developed a

current capability design for manufacturing framework in the aerospace industry, utilizing the IDEF0 map to analyze the procedure to achieve Design for Manufacturing and Assembling (DFMA), which makes the procedure clear and easy to understand.

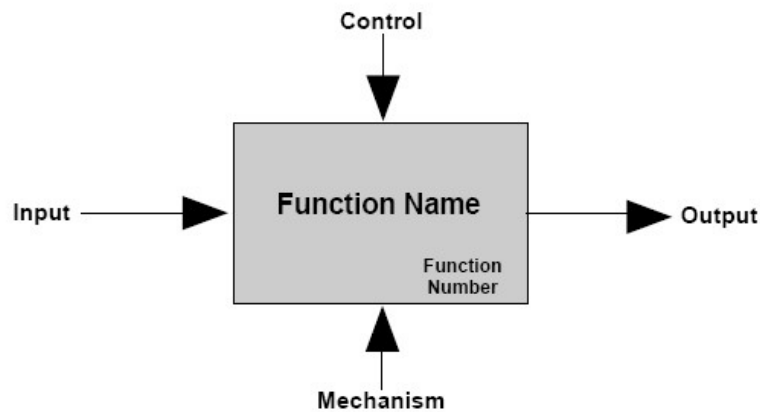


Figure 2-7 Schematic diagram of basic IDEF0 map (Defense Acquisition University, 2001)

## 2.3 Laser Beam Welding

Laser beam welding (LBW) is a fusion welding process that results in the joining of two or more pieces of material (usually metal) by the interaction of the concentrated laser beam and the material surface (Tamarit, 2010; American Welding Society (AWS), 2010). It is a low heat input and high density welding process. The first study of LBW was in the early 1960s, but this technique had not been widely accepted until the development of high power CO<sub>2</sub> lasers in the early 1970s (Duley, 1998).

### 2.3.1 Laser Beam Welding Principle and Laser Types

The laser beam is focused onto the surface of the workpiece and heats the focused area. The material starts to melt at the melting point and evaporate when the temperature increases to the boiling point. A keyhole is formed which leads to a strong increase in beam absorption while the power is above a certain intensity. The threshold intensity to ignite this process depends on the material and the normal absorptivity. The principle of LBW is presented in Figure 2-8.

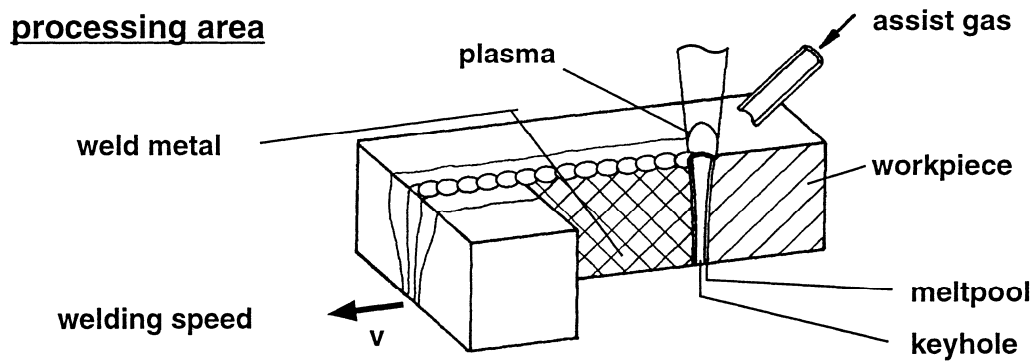


Figure 2-8 Principle of Laser Beam Welding (Behler et al., 1997)

The laser beam is a heat source, which limits the heat to small areas and raises the speed of both the heating and cooling processes. Solid and gas are alternative active medias for welding lasers. According to this, two types of lasers are referred to as “solid state lasers” and “gas lasers”. Solid state lasers operate on a much shorter wavelength than gas lasers, but they have much lower power outputs. The commonly used solid state laser and gas laser in industry are carbon dioxide (CO<sub>2</sub>) and Neodymium-doped Yttrium Aluminium Garnet (Nd: YAG) lasers, respectively. Table 2-2 presents a simple comparison between these two lasers, characteristics such as beam power and wavelength are illustrated.

Table 2-2 Comparison between CO<sub>2</sub> and Nd: YAG welding lasers (AWS, 2010; Behler et al. 1997)

Type	CO <sub>2</sub> laser	Nd: YAG laser
Active medium	CO <sub>2</sub> , N <sub>2</sub> , He (gases)	Nd:YAG Crystal
Wavelength	10.6 μm	1.06 μm
Beam power	0.1-45 kW	0.1-5.5 kW
Pulse frequency	CW-100	CW-50
Efficiency	5-15%	1-4%

### 2.3.2 Laser Beam Welding Modes and Methods

There are two distinctly different modes of LBW which are commonly referred to as conduction mode welding and keyhole mode welding (Duley, 1998; AWS, 2010). The basic difference between these two methods is the power intensity and the resultant geometry of the Heat Affected Zone (HAZ).

For conduction welding mode, as the power density is lower than the threshold density for penetration, the incident beam power on the surface is transferred to the root of the weld by conductive and convective heat flow in the molten metal. The maximum aspect ratio (weld depth divided by weld width) is low, commonly between 0.5 and 1.0 only (AWS, 2010). Keyhole welding occurs when the laser power density is greater than the threshold density. The material at the interaction point melts and vaporizes. Thus, the weld pool opens up to allow the laser beam to enter the melt pool and a deep cavity (keyhole) is formed. The aspect ratio for keyhole welding could range from 1.0 to greater than 10.0 (AWS, 2010). The HAZ for conduction welding and keyhole welding is illustrated in Figure 2-9. Most advantages of LBW, such as narrow HAZ and low distortion, are related to keyhole welding and this is the main reason that LBW became widely accepted after the development of high power CO<sub>2</sub> lasers.

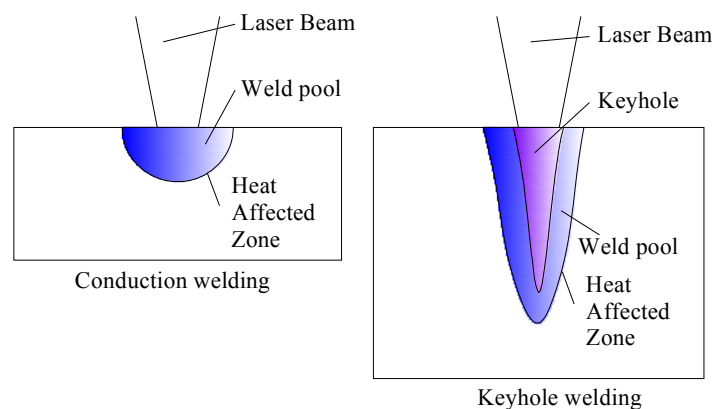


Figure 2-9 Comparison between conduction welding and penetration welding modes (AWS, 2010)

Regarding the difference of energy sources, LBW can be classified as single beam welding, dual beam welding and Laser-X hybrid welding (X is another welding method, such as Arc welding). For butt joints and lap joints, single beam LBW is the common welding method. However, for a T butt joint, dual beam welding is preferred for lower distortion resulting from symmetric welding. Single beam welding for this configuration easily causes residual stress and distortion (Duley, 1998). Figure 2-10 illustrates schematic diagram of single beam and dual beam welding for T butt joint. The dual beam welding in this situation is a symmetrical welding from both sides of the T butt joint.

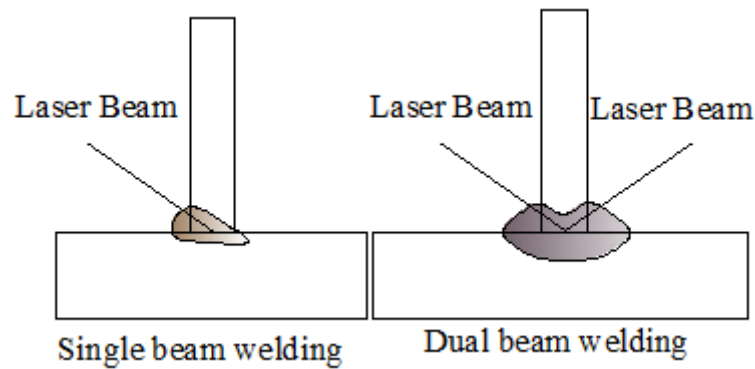


Figure 2-10 schematic diagram of single beam and dual beam welding for a T butt joint

Laser-X hybrid welding combines the advantages of both welding technologies because it introduces a secondary energy source to the weld pool area. For example, the Laser-Arc welding combines typical laser welding benefits—high travel speeds, limited HAZ and narrow weld joint—with those of arc welding: process energy efficiency and gap-bridging. The disadvantages are increased investment costs and limited accessibility which are brought with arc processes. (Green, 2005) This welding method can be applied in both single beam welding and dual beam welding.

### 2.3.3 Laser Beam Welding: Advantages and Disadvantages

Many advantages for LBW have been identified through the literature, compared to riveting and traditional welding process, such as Gas Metal Arc (GMA) welding. Some comparisons between them are analyzed and illustrated in Table 2-3 according to Andersen et al. (2001), Schneider and Schumacher (2002) and Kocak and Uz (2009). The comparison between LBW and riveting is based on the aircraft industry whilst the comparison between LBW and GMA welding has no special industry background.

Compared with riveting, the significant advantages of the LBW process include weight reduction of the aircraft fuselage panel structure, operation cost saving and corrosion resistance improvement. The weight reduction is due to lower density alloys, reduced mass of sealing, simplified stringer and partial reduction of rivets weight. It is supposed to be able to gain 5% (Brenner, 2008) to 10% (Andersen et al., 2001) of weight reduction. The operation cost saving is due to

reduced mass of material, high grade of automation and reduced manufacturing steps. It is supposed to be able to gain 15%- 20% (Andersen et al., 2001) of overall cost reduction. The corrosion resistance improvement is due to elimination of risk from rivet holes and absence of gaps (Andersen et al., 2001; Schneider and Schumacher, 2002; Mendez and Eagar, 2002; Kocak and Uz, 2009).

Table 2-3 Comparison between Laser Beam Welding (LBW), Gas Metal Arc welding (GMA) and Riveting

<b>Process</b> <b>Aspect</b>	<b>GMA</b>	<b>LBW</b>	<b>Riveting</b>	<b>Automatic riveting</b>
<b>Weight saving</b>	/	+	-	-
<b>Corrosion resistance</b>	/	+	0	0
<b>Fixture</b>	/	+	-	-
<b>Operation cost</b>	+	0	-	0
<b>Heat-affected zone</b>	-	+	/	/
<b>Distortion</b>	-	+	/	/
<b>Production rate</b>	0	+	-	0
<b>Automate process</b>	0	+	-	+
<b>Capital cost</b>	+	-	+	-

Key: +: advantages; -: disadvantages; 0: neutral; /: not compared

Other advantages, such as improvement of production rate and simplicity of fixture are also remarkable. Generally, the LBW speed can be 8 m/min to 10 m/min while the comparable riveting process is only 0.15m/min to 0.25 m/min (Rendigs and Knowler, 2010). It is stated that tooling for LBW process is very simple and flexible. A holding fixture (Figure 2-11) is required. The guiding and clamping unit is integrated within the welding system, whilst the riveting fixture is usually complex, constructed with locator and clammer for every workpiece being assembled and a fixture frame. Figure 2-12 shows a typical riveting fixture for panel assembly in aircraft industry.



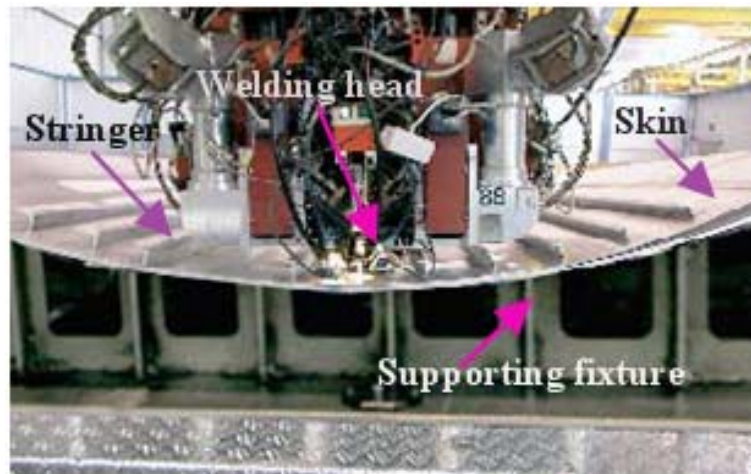


Figure 2-11 A typical fixture for Laser Welding (Rendigs and Knowler, 2010)

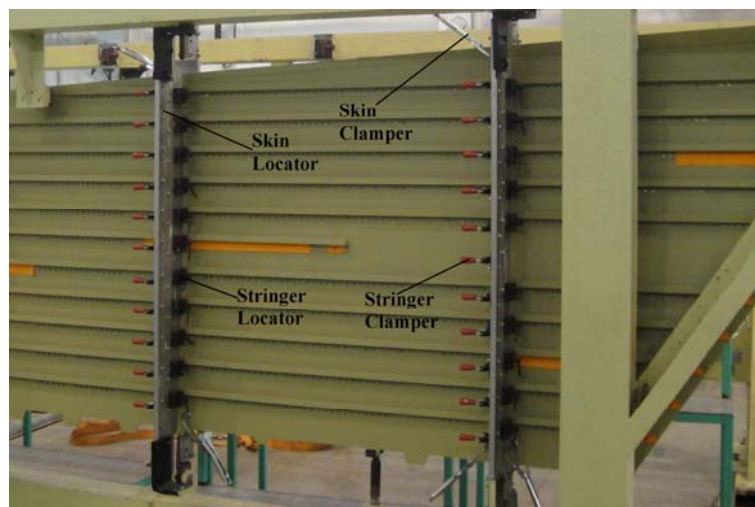


Figure 2-12 A typical fixture for riveting panel assembly (Source: COMAC)

Comparing with GMA welding, the LBW process gains more advantages from high power density and welding speed, such as small Heat Affected Zone (HAZ), low distortion, high joint strength and high production rate (Dawes, 1992; Schneider and Schumacher, 2002).

The high capital cost of an LBW system is the first barrier to this technology for most companies. However, the Laser system can also be used for other processes, such as cutting, surface hardening, machining drilling and trimming, by varying the power density (Walz, 2002). If the system can be shared by some of these processes, the capital cost would be shared too. This will be helpful for the decision to implement LBW in the aircraft industry, although the aircraft industry is not a batch production in general. Other advantages and disadvantages of LBW identified from the literature are listed in Table 2-4.

Table 2-4 Advantages and disadvantages of Laser Beam Welding (Dawes, 1992; Schneider and Schumacher, 2002)

Advantages	Disadvantages
<ul style="list-style-type: none"> <li>✚ Deep narrow welds;</li> <li>✚ High process flexibility;</li> <li>✚ Enhanced component design opportunities;</li> <li>✚ Weld dissimilar material &amp; thickness;</li> <li>✚ Atmosphere welding possible.</li> </ul>	<ul style="list-style-type: none"> <li>✚ Close fitting and well clamping required;</li> <li>✚ Exact positioning required;</li> <li>✚ Accurate beam/joint alignment needed;</li> <li>✚ Restricted penetration depth (25mm);</li> <li>✚ High power consumption.</li> </ul>

### 2.3.4 Laser Beam Welding Materials

LBW offers the possibility to manufacture joints of most light metals and their combinations, such as aluminium, magnesium and titanium, because of its high energy density (Schubert et al., 2001). In order to spread the application of LBW in the aircraft industry, many aluminium alloys have been studied by researchers and some have already been applied to the industry over the last 10 years. Partial materials are listed in Table 2-5, including some 5xxx series and 6xxx series aluminium alloys and Al-Li alloys.

Table 2-5 Partial materials studied for LBW

Aluminium alloy	Source
<b>6013/6056/6156</b>	Rendigs and Knowler, 2010
<b>5083, 5059, 6082</b>	Ancona et al., 2002
<b>6110 T61</b>	Galantucci et al., 2000
<b>Al--Li 2091-T8X</b>	Lin, 1988
<b>Al--Li 2090</b>	Molian and Srivatsan, 1990
<b>5A90</b>	Xu et al., 2009
<b>A hybrid Ti-Al structure</b>	Möller et al. 2011

With the increase of laser power, most aluminium can be welded now nevertheless the weld performance is variable. Most 6xxx series Aluminium

alloys as well as Al-Li alloys shows good weldability according to these literatures. The main characteristics of these aluminums, which influence LBW, are hydrogen solubility, thermal conductivity, thermal expansion and solidification shrinkage (Mandal, 2002). Moisture or hydrocarbons on the surface might create hydrogen and this is the main source of porosity in aluminium welds whilst the cleanliness of the filler metal is another consideration. High thermal conductivity requires a high rate of heat input for fusion welding and this is why aluminium is considered difficult to weld using a conventional welding process. Solidification shrinkage in an aluminium weld metal is about 6% by volume and it can be the main cause for distortion, especially for thick welds. Although the 6xxx series alloys are prone to hot cracking, this condition can be overcome by correct choice of joint design and parameter. Furthermore, the strength of the Heat Affected Zone (HAZ) can be improved through post-welding heat treatment.

### 2.3.5 Laser Beam Welding Structure

The airframe structure is supposed to be designed to be as light as possible within the strength limitation. The commonly used joint types for a riveted fuselage panel are illustrated in Figure 2-13.

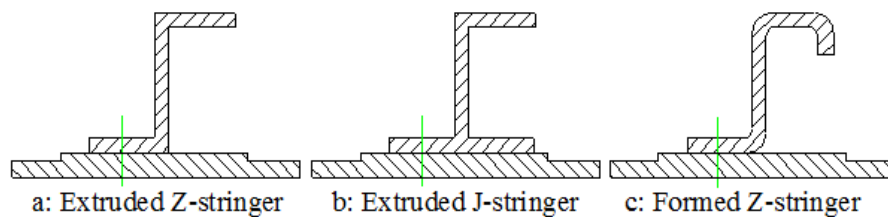


Figure 2-13 Common used joint types for riveted fuselage panel (Niu, 1988; Tempus, 2001; Rendigs, 2010)

Because of the utilization of LBW, the wide rivet straps in the aircraft skin and at the butt end of the stringer are no longer required. It also eliminates the need for a filler metal between the riveted parts if they are closely contacted. Figure 2-14 illustrates a comparison between the structure design of a skin-stringer joint for riveting and LBW, respectively. A differential structure is utilized for riveting whilst an integral structure is applied to LBW. The conventional “Z” type stringer

is simplified to an “L” type stringer, which gives the advantage of a weight reduction of the fuselage panel.

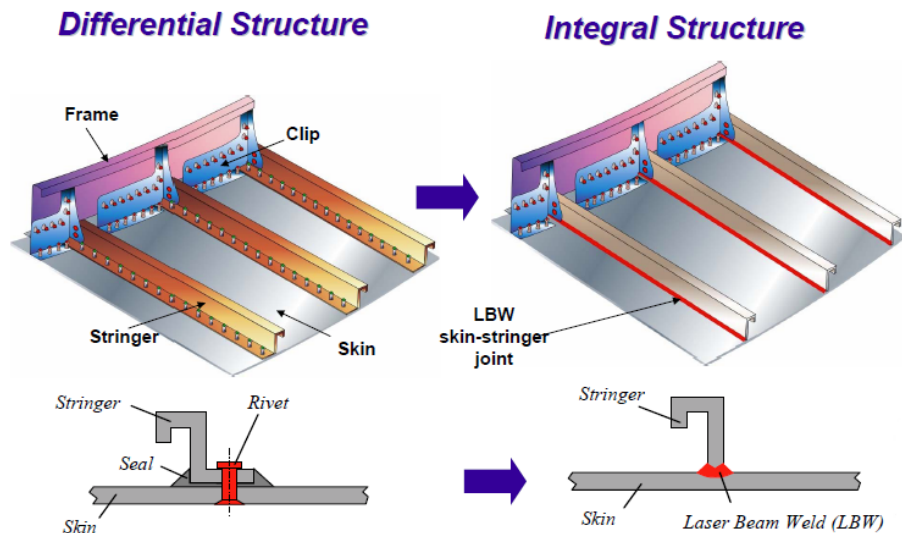


Figure 2-14 Comparison between skin-stringer joint design for riveting and Laser Beam Welding (Kocak and Uz, 2009)

Tempus (2001) supposed a stringer root thickened structure for welding joints within the fuselage panel as shown in Figure 2-15. In this structure, the area of contact with the stringer root on the skin is thickened a certain thickness, so the skin itself will not be influenced by the LBW process because of small HAZ. This method is similar to the robust skin thickness for riveting. The only problem is to decide the dimension of the robust skin area, which will be discussed in chapter 6. This T butt joint can be constructed with extruded stringer and chemically milled skin, and simultaneous welding from both sides. Furthermore, this structure type is going to be used for a pilot production of seat rails with such dissimilar materials as titanium and aluminium, which is shown in Figure 2-16 (Pacchione and Telgkamp, 2006).

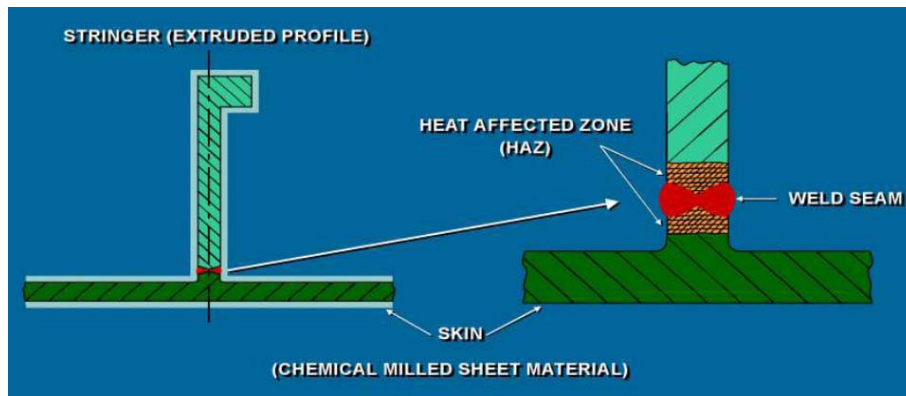


Figure 2-15 Stinger root thickened structure (Tempus, 2001)

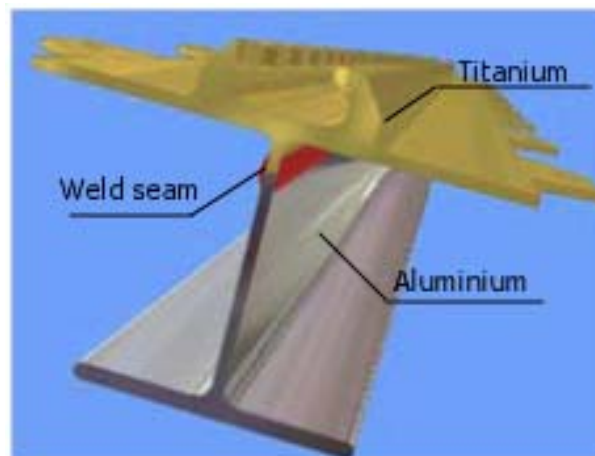


Figure 2-16 Dissimilar welding of titanium and aluminium for seat rails  
(Pacchione and Telgkamp, 2006)

### 2.3.6 Laser Beam Welding Process Parameters

It is found that a stable LBW process depends on defining and controlling the processing parameters which influence process stability to reliably produce high quality welds at high welding speeds (Cao et al. 2005). Thus, the LBW process parameters and their effects on LBW quality have been widely studied during the last ten years. Some of the studied parameters are reviewed and listed in Table 2-6.

Table 2-6 Reviewed Laser Beam Welding process parameters

Process parameters	Laser power	Welding speed	Focal optics	Gas	Filler metal	Joint preparation
Haferkamp et al., 2000						√
Haferkamp et al., 2001					√	
Watkins and Kaplan, 2003					√	
Cao et al., 2005	√		√			√
Wang and Li, 2006	√	√		√		
Al-Kazzaz et al., 2008		√				
Padmanaban and Balasubramanian, 2010	√	√	√			
Deng and Kiyoshima, 2010						√
Patschger et al., 2011				√		

It has been identified by many researchers and engineers that the laser power, welding speed and focal position are the most important process parameters for the LBW process. They are related to a hidden parameter called energy density which is a key factor of penetration welding and will influence the weld formation. Too high energy density will result in an unstable keyhole which can cause drop through while too low energy will not permit penetration welding. Some of the influences are illustrated in Figure 2-17 according to the literature listed in Table 2-6.

It is found that laser power determines the weld width and depth, and is crucial for keyhole welding (Cao et al., 2005; Wang and Li, 2006). The threshold power density for keyhole welding is a consequence of the different beam spot size at the surface and the laser power. Welding speed is another parameter that determines the weld width and depth, and it influences the weld fusion depth (Al-Kazzaz et al., 2008; Padmanaban and Balasubramanian, 2010). Focal position is related to the weldability of workpiece thickness and is suggested to set where the maximum penetration depths or best process tolerances are produced (Cao et al., 2005). All these three parameters are found to have great influence on tensile strength on the welds.

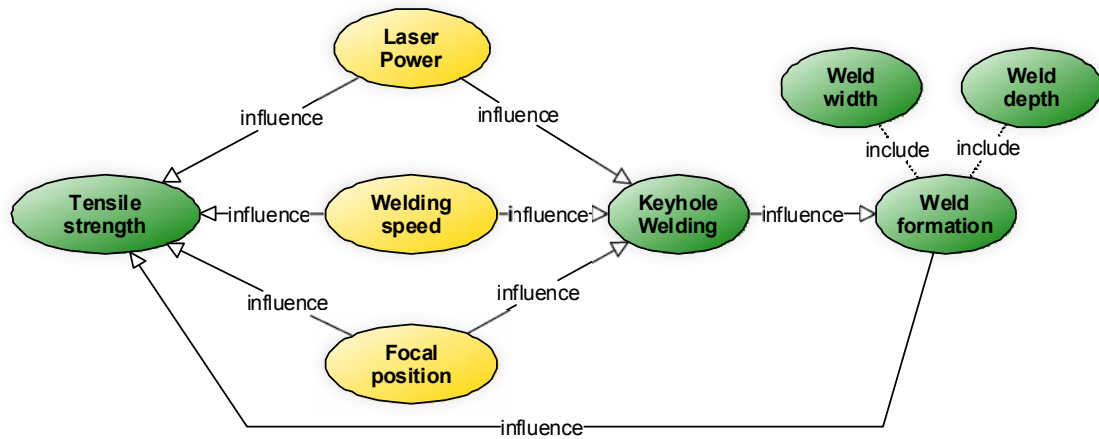


Figure 2-17 Influence of laser power, welding speed and focal optics

Other process parameters such as protection gas, filler metal and joint preparation have been found to influence final welds too. Their effects are illustrated in Figures 2-18, 2-19 and 2-20, respectively.

The utilization of protection gas could reduce oxidation, pores and obtain a better root surface quality through preventing contact between weld pool and atmosphere, protecting the transmission of the laser beam and controlling the molten metal flow. It also has a slight effect on the weld width, and directly affects the surface colour of the welds. Using different shielding gas can optimize the process with regarding to seam formation. Helium is the preferred shielding gas for its high thermal diffusivity, but it is also the most costly. Thus, a mixture of argon and helium are often used to reduce the cost (Wang and Li, 2006; Patschger et al., 2011).

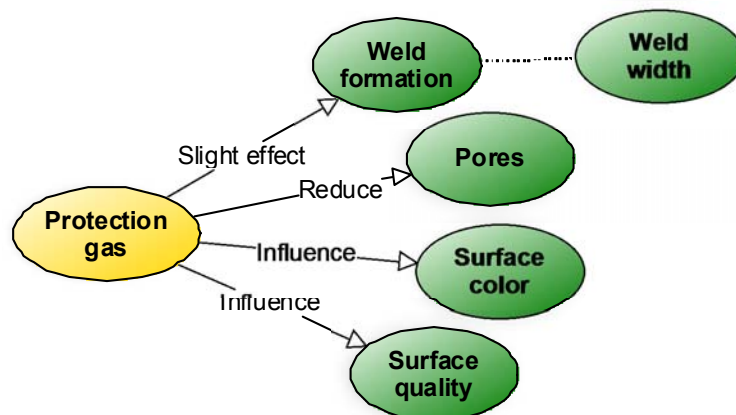


Figure 2-18 Influence of protection gas

Filler metal is often used in condition of higher power and lower weld speed because the filler will absorb part of the power. It can promote process stability,



reduce porosity, lower the sensitivity to joint gaps and widen the fusion zone slightly through the adding of alloying elements to the weld (Haferkamp et al., 2001; Watkins and Kaplan, 2003).

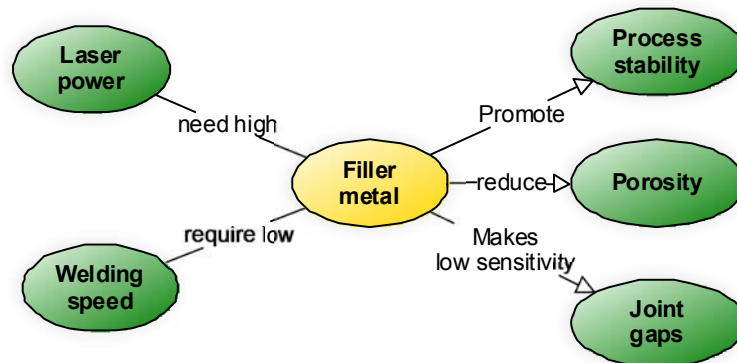


Figure 2-19 Influence of filler metal

The surface condition may influence the energy absorption of incident laser beams so as to affect the threshold power density for keyhole welding. So a polished surface is not preferred for LBW because of its high reflectivity. The initial residual stresses prior to welding have significant effects on the residual stresses after welding (Deng and Kiyoshima, 2010). The elimination of moisture, oil and dust plays an important role in achieving high weld quality because they will induce defects to the weld; one example of this is hydrogen pores (Haferkamp et al., 2000; Cao et al., 2005).

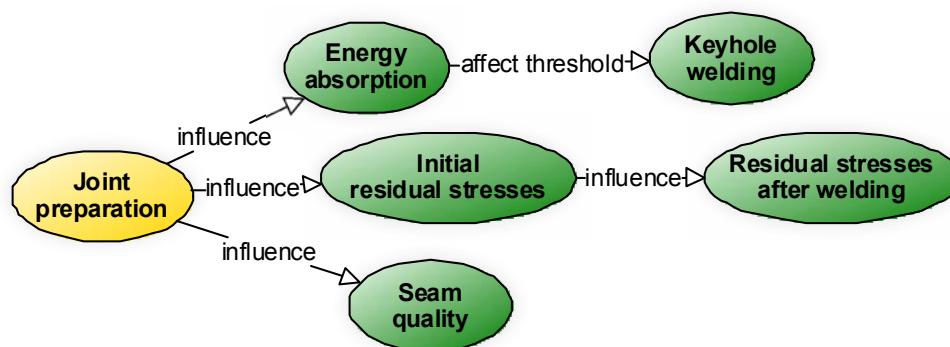


Figure 2-20 Influence of joint preparation

All these parameters are interactive, especially the laser power, focal position and welding speed. For example, for a given focal position and material thickness, the higher the power, the faster the welding speeds. It can be concluded from the previous introduction that selecting appropriate process parameters is essential for achieving optimal welding quality. It also has been



suggested that all the welding area on the workpiece as well as the filler metal should be cleaned to remove moisture, oxide and hydride layers, as well as any dirt (Oates, 1996; Jutter, 1997; Haferkamp et al., 2000).

### **2.3.7 Laser Beam Welding in the aircraft industry**

The idea of LBW in the aircraft industry was first raised in Russia in 1989 for skin-stringer joining and the first production shell was approved in 2001 for the A318. AIRBUS, EADS and Institut für Werkstoff- und Strahltechnik (IWS) have made a great effort to the application of LBW in pressurized fuselage manufacturing. Figure 2-21 illustrates LBW of stringer to skin in spherical shaped shells for Airbus A318 (Pacchione and Telgkamp, 2006). Since 2010, more than 1200 shells for the A318, A340 and A380 have been produced (Rendigs and Knower, 2010). It is purposed to use LBW for the A350. The utilization of LBW in these airplanes is illustrated in Table 2-7, from which a conclusion can be got that the application of LBW in the Airbus is increasing rapidly.

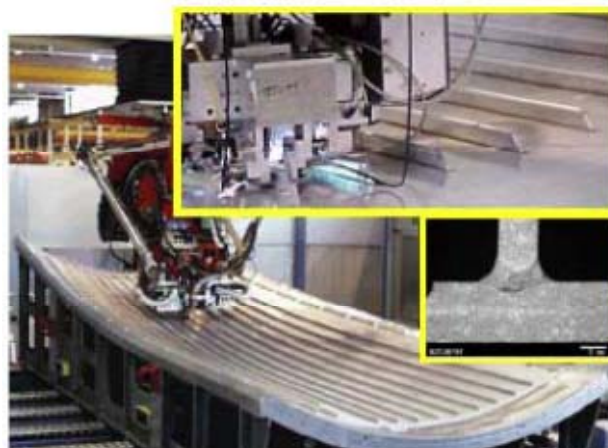


Figure 2-21 Laser Beam Welding of stringer to skin in spherical shaped shells for Airbus A318 (Pacchione and Telgkamp, 2006)

Table 2-7 Application of Laser Beam Welding in the Airbus

	Material	Structure	Seam length	First shell
<b>A318</b>	6013 & 6056	1 fuselage panels	110m	2001
<b>A380</b>	6056&6156	8 fuselage panels	650m	2003
<b>A340-HGW</b>		14 fuselage panels	798m	2004
<b>A350</b>		18 fuselage panels	1000m	

According to this evidence, the LBW process in the aircraft industry should be a mature process now. Results from the questionnaire in chapter 5 also verified that welding in primary aerospace structures is well accepted, however not widespread in use.

Figure 2-22 shows LBW equipment for low fuselage panel batch production in Airbus-Nordenham (Tempus, 2001). By using this advanced equipment, the production is completely easy and automatic with only a few steps. In the first step, the engineer scans the CAD data of the components that are to be joined together. They then create a CNC program to control the action of the 21 axes of movement. After this, the skin section is tautened by vacuum clamping and the seam tracking sensors are calibrated. When the two laser beam foci have been directed at the welding point, the stiffening stringer is inserted into the stringer clamping and guiding unit (Figure 2-23) (Fraunhofer magazine, 2001). The CNC program is started, and the welding process begins.



Figure 2-22 Equipment for low fuselage panel batch production (Tempus, 2001)

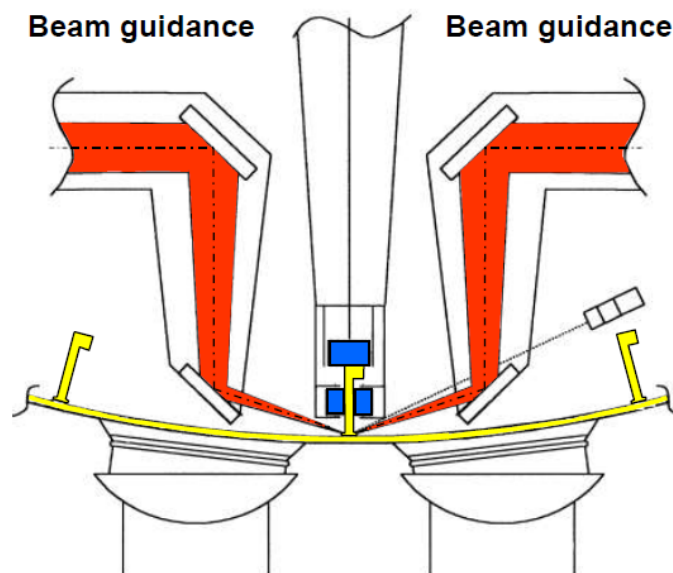


Figure 2-23 Stringer guiding system (Rendigs and Knowler, 2010)

## 2.4 Aircraft Industry Product Development

The product development procedure in the aircraft industry is developing fast and becoming more and more integrated because of the development of new material, advanced technology and improved design principles. A significant change has come from the development of concurrent engineering, which results in a reduction of the product development cycle (Curran et al., 2002). The traditional procedures as well as the procedures in the condition of Concurrent Engineering (CE) will be reviewed in section 2.4.1 and section 2.4.2, respectively.

### **2.4.1 Traditional Product Development Procedure**

The traditional product development procedure in the aircraft industry follows a linear flow, constructed with marketing, design, process planning, manufacturing and testing until reaching full production in general, which is illustrated in Figure 2-24 (Curran et al., 2002; Kessler and Kos, 2005; COMAC, 2009).

In the marketing stage, customer requirements are collected, analysed and transformed into initial design constraints. The design stage can be divided into three phases: concept design, primary design and detail design. Design analysis and a trade-off study are essential in this stage to ensure its feasibility from technique and economic aspects. The manufacturing stage can also be further categorized as three aspects: part fabrication, sub-assembling and final assembling. The final assembling includes not only the structure assembling but also installation of functional systems. The fabrication of an aircraft is a procedure to assemble small parts into large component, larger sub-assemblies and finally the huge aircraft. Different components with different materials always need different methods or processes for fabrication. For example, composite components are always built up with forming, laying-out, joining and metal bonding, whilst some aluminium fuselage panels can be fabricated using LBW. Process planning is an essential stage to link the design and manufacturing and ensure that the product can be achieved within the design requirements. The fabrication methods as well as the process parameters should be defined in this stage. Furthermore, process analysis and trade-off study should also be conducted to ensure its feasibility. Testing is a necessity for each of the parts, components and sub-assemblies as well as the whole aircraft, both for structure strength and system function.

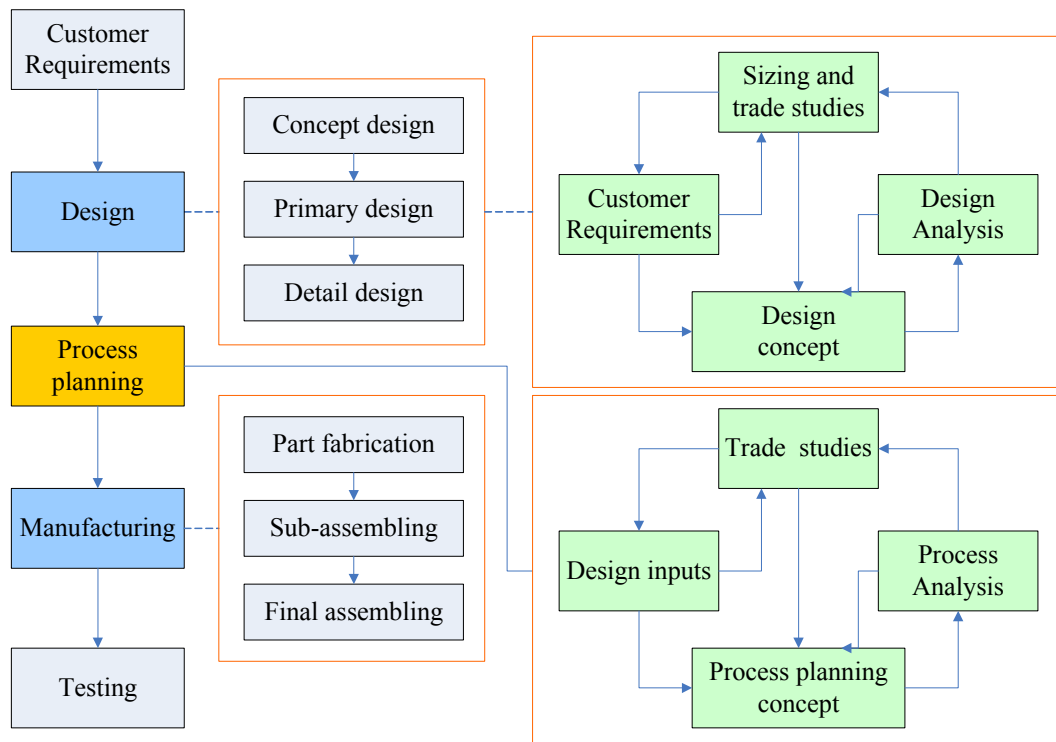


Figure 2-24 Traditional aircraft industry product development procedure and strategy (Curran et al., 2002; COMAC, 2009)

Figure 2-25 illustrates a simplified vertical business layout of an aircraft manufacturing company which is suitable for the traditional development procedure. The definition of department is according to the functional requirement. Tasks with a certain project shift from design to manufacture only when the design procedure has been finished. Whiteside (2008) indicated that the sequential nature of these operations often results in an extended lead time. Interdepartmental communications and other non-value added activities such as correcting designs that have manufacturing issues cause waste of resources. To avoid or reduce these limitations is the major motivation for the application of CE to this field which will be introduced in section 2.4.2.

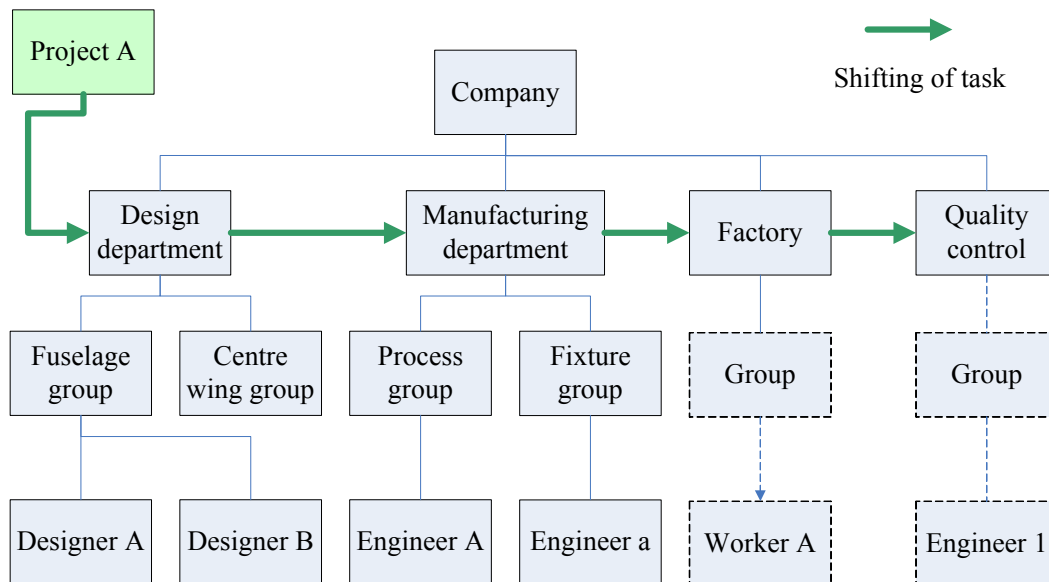


Figure 2-25 A simplified demonstration of vertical business layout (Swift and Brown, 2003; COMAC, 2009)

## 2.4.2 Concurrent Engineering

The days of an engineering organization creating a new design and then “throwing it over the wall” to manufacturing are over. Today, most products are developed by integrated teams which include both design and manufacturing personnel – working at the same site or different sites (Shalvi, 2003). The concept of integrated functional teamwork is known as CE (Whiteside, 2008).

The improved product development procedure in the aircraft industry in the CE environment is illustrated in Figure 2-26, where the design and process planning as well as manufacturing is parallel to a certain extent. Analysis and trade-off study of both the design and process should be conducted in this parallel development procedure for the feasibility and balance of technique and economics. CE can be deployed throughout the procedure (Roy et al., 2001). However, it is especially effective and feasible at the concept stage where design, manufacture and cost can be examined simultaneously. The development of Computer Aided Design (CAD), Computer Aided Engineering (CAE) and Computer Aided Manufacturing (CAM) further facilitates its implementation because the application of these methods makes the designers and engineers have more knowledge in common.

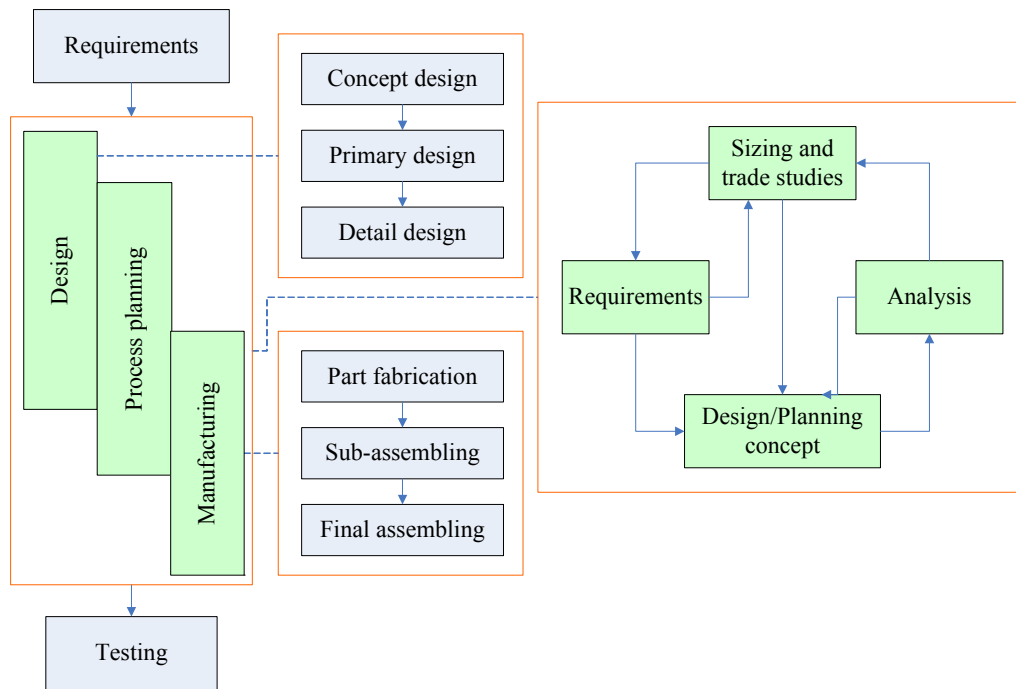


Figure 2-26 Aircraft industry product development and strategy for Concurrent Engineering (Curran et al., 2002; COMAC, 2009)

The development of CE moves companies away from the vertical business layout towards a matrix layout which also promotes cross-functional integrated product teams. A simplified matrix business layout in the aircraft industry is illustrated in Figure 2-27. In this layout, the personnel should take responsible to both the project team and department. Because an integrated functional team is built for a certain project or task, it will bring significant benefits to the Design for Manufacturing and Assembling (DFMA) methodologies (Swift and Brown, 2003).

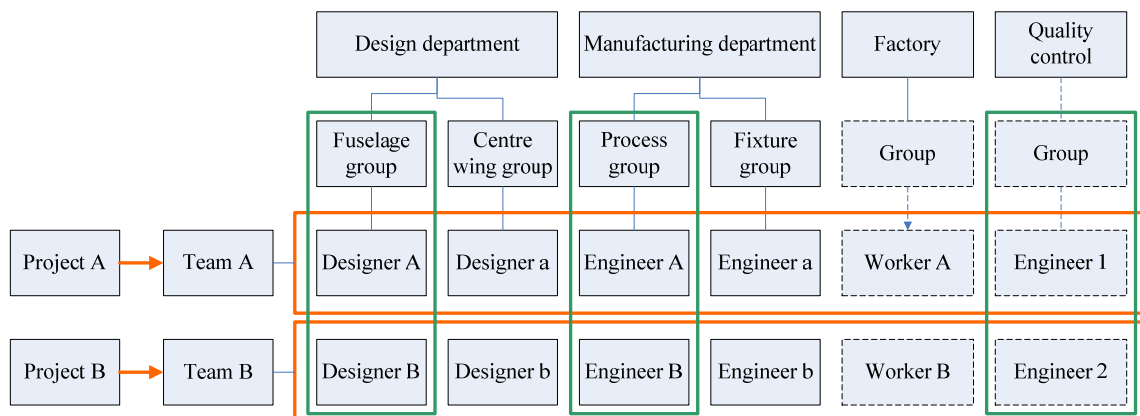


Figure 2-27 A simplified demonstration of matrix layout (Swift and Brown, 2003; COMAC, 2009)

## 2.5 Existing research on Knowledge Modelling

Mohammad et al. (2010) proposed two different frameworks to capture tacit and explicit knowledge, which are general, concise and cost efficient, and could be used by most large organizations. They are not suitable for this project because they lack particularity for the aircraft industry. However, some methods and ideas can be used in this project, such as interview for tacit knowledge capture. Figure 2-28 shows a simplified framework for tacit knowledge capture as proposed by Mohammad et al. (2010).

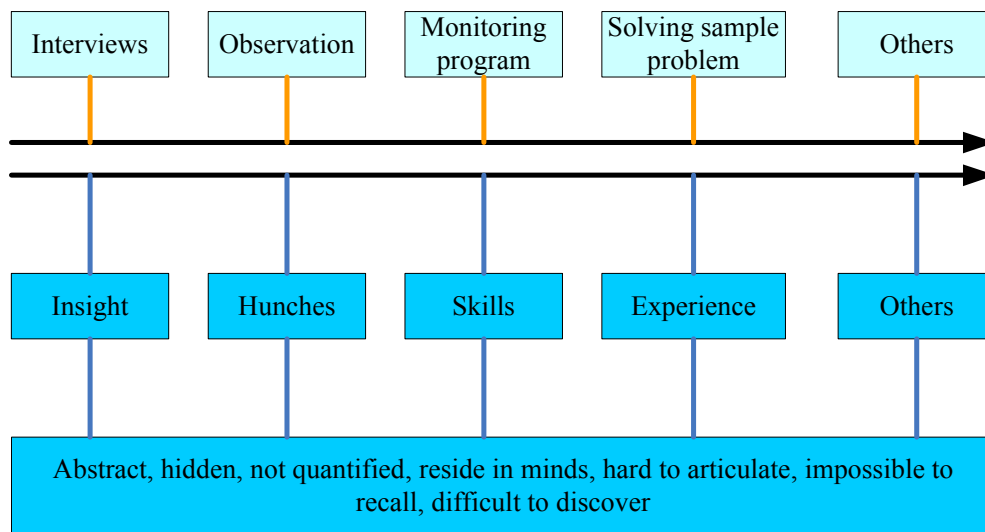


Figure 2-28 Framework for tacit knowledge acquisition (Mohammad et al., 2010)

Whiteside (2008) developed a current capability design for a manufacturing framework in the aerospace industry, describing how to create a capability forecast for the requirement of a model through a translation of capability performance data. This framework has described the procedure to implement a Design for Manufacturing and Assembling (DFMA) method but has not explained how to capture the current capabilities in detail. IDEF0 is utilized for the process modelling of this approach and makes the whole procedure clear and simplified.

Tamarit (2010) proposed a four-step procedure to knowledge modelling of joining/ welding processes, i.e. field study, interview, collect and analyze data, and represent the captured knowledge, as illustrated in Figure 2-29. In this research, the captured knowledge for spot welding, LBW and adhesive bonding processes in the automotive sector have been represented as rules and



recommendations. This method has also been used by Lamacchia (2010) in a study entitled “Design of joining tools for lean manufacturing”. In his study, IF-THEN rules have been used to capture and represent knowledge about joining tool design. This method can be chosen for this project too, as rules and recommendations are commonly used to guide the product design and development and are liked by most engineers in the aircraft industry.

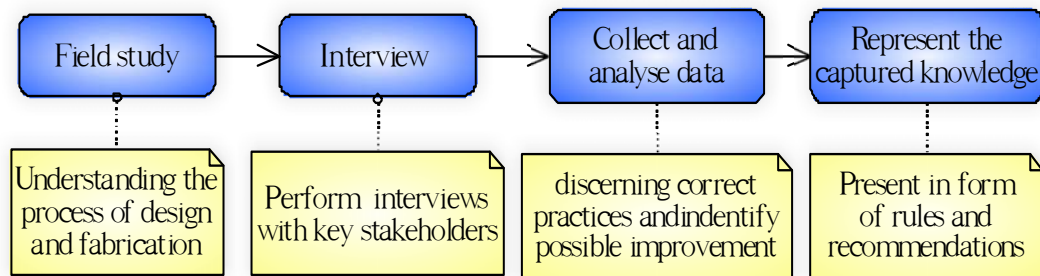


Figure 2-29 Knowledge modelling of joining/welding processes (Tamarit, 2010)

## 2.6 Research gap analysis

Like any other moving vehicles industry, weight reduction is always the main concern for economic efficiency in the aircraft industry. Thus, most structures on the aircraft are intended to be designed and built light as well as strong, which makes these structures difficult to fabricate. LBW is a possible solution to solve this problem and so has been studied by many researchers. Much research about the effect of process parameters on weld properties or qualities for a certain material has been found during literature review, which is based on experiments. For example, Ancona et al. (2007) studied the welding reliability of butt-joints on process parameters through experiments on 3-mm thick aluminium–magnesium alloy 5083 specimens, and found that the welding reliability was enhanced by optimization of parameters. Wang and Li (2006) studied the effect of laser power and welding speed on weld properties and found that the micro-hardness and tensile strength of the weld zone are better than that of the base metal, AZ61 magnesium alloys. The literatures about knowledge modelling of the LBW process are much less than the previous type. Studies based on automotive industry from Tamarit (2010) and Lamacchia (2010) were found and introduced in section 2.5. Little evidence shows that there is existing research about knowledge modelling of the LBW in the aircraft industry.

After analysing the existing researches, some research gaps have been identified:

- There is little published work on the knowledge model for the LBW process in the aircraft industry;
- There is little published rules and recommendations for LBW structure design and process planning in the aircraft industry.

## **2.7 Summary**

A comprehensive literature review has been conducted in this chapter, covering three domains: knowledge modelling, Laser Beam Welding and aircraft industry product development. This contributes to the selection of methods and tools for knowledge modelling. Interview, concept mapping, rules and recommendations as well as UML and IDEF0 are chosen for this research as they are standard and commonly used methods for knowledge modelling. Little evidence shows that there is existing research about knowledge modelling of the LBW in the aircraft industry with rules and recommendations. The identified research gaps have verified the research motivation and driven the author to focus on the establishment of rules and recommendations.

## **3 Research Methodology**

### **3.1 Introduction**

There are several different research methodologies available for conducting researches. It is important to define and adopt the most appropriate one for a particular research in order to best exploit the information and data. This chapter describes the selection of the methodology, which includes four primary stages to build and validate the aimed knowledge model.

### **3.2 Research Methodology Adopted**

Generally speaking, quantitative and qualitative methods are two principle types of research methods. Quantitative research method is used when the reality is objective, concentrating on statistics and following a deductive method to collect evidence to substantiate existing ideas and theories. In contrast, qualitative method involves more subjective and opinion driven data, following an inductive approach to derive a theory or conclusion (Whiteside, 2008).

An inductive approach is followed in this research to build the knowledge model for the LBW process in the aircraft industry based on a literature review and investigation of practice. Thus, a qualitative methodology was adopted in this research, using the primary tools of interviews, questionnaire, literature review, concept mapping, rules and recommendations, IDEF0 and UML to build the knowledge model. Figure 3-1 illustrates the structure of the research methodology, consisting of four major phases. The tasks and outputs for each phase are also presented.

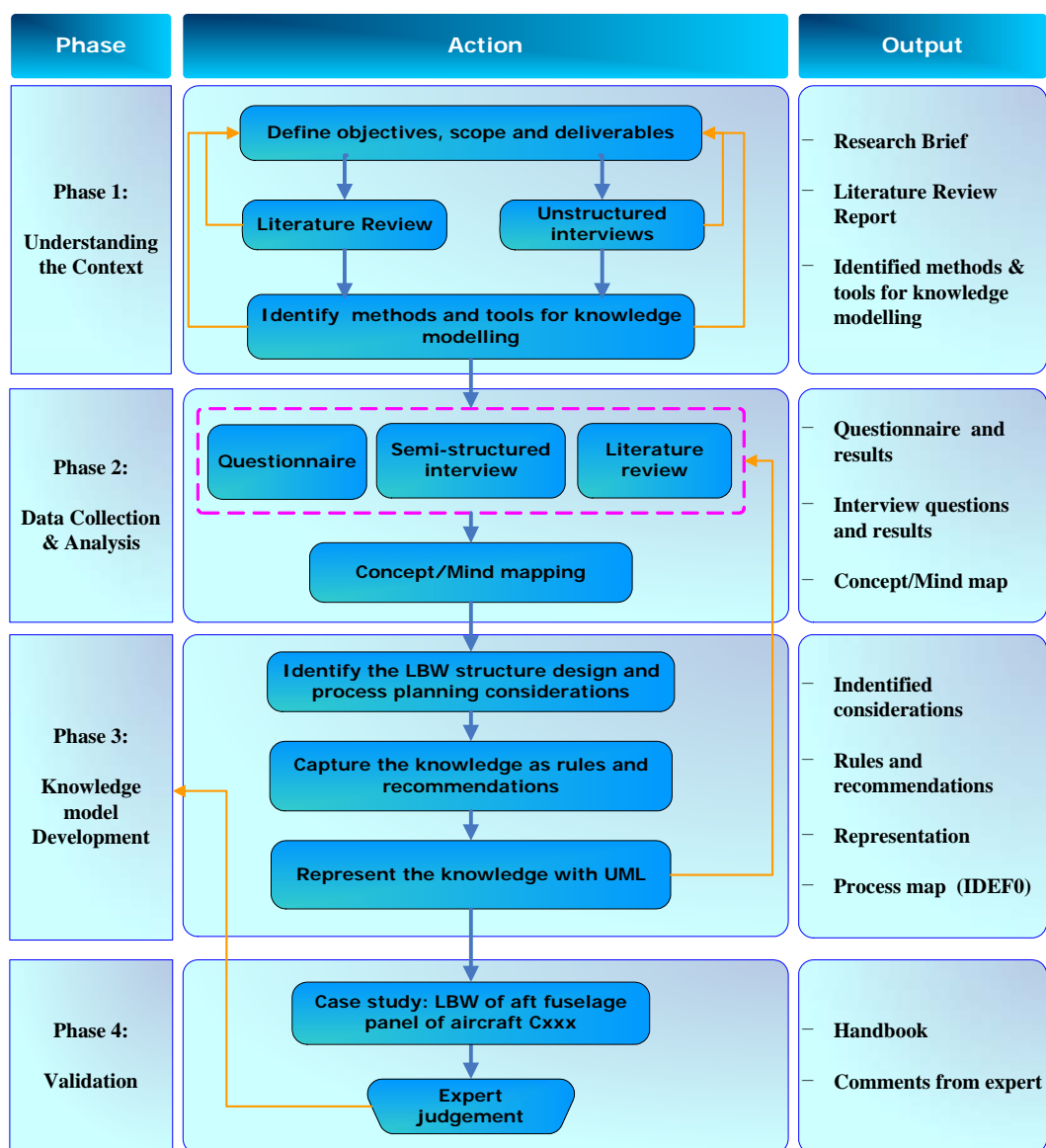


Figure 3-1 Research Methodology Adopted

### 3.3 Phase 1: Understanding the Context

The main tasks in this phase are to obtain a clear understanding of this research topic and to identify the knowledge modelling methods and tools for this project. An initial literature review and a series of unstructured interviews with specialists from the Commercial Aircraft Corporation of China (COMAC) by Web conference, telephone and emails were conducted for this purpose. Additionally, a short course entitled “Knowledge creation” and a Lean Product and Process Development (LeanPPD) workshop at Cranfield University were attended during this term, which also contributed to the methods and tools identification. The key tasks, tools and outputs in this phase are listed in Table 3-1.

Table 3-1 Key tasks, tools and outputs in phase 1

<b>T1.1. Gain a brief understanding of the context</b>	
Tools and methods	<ul style="list-style-type: none"> <li>• Initial literature review</li> <li>• Unstructured interview</li> </ul>
Outputs	<ul style="list-style-type: none"> <li>• Brief understanding of knowledge modelling and LBW</li> <li>• Literature review report</li> </ul>
<b>T1.2. Identify the methods and tools for knowledge modelling</b>	
Tools and methods	<ul style="list-style-type: none"> <li>• Unstructured interview</li> <li>• Taking Short course</li> </ul>
Outputs	<ul style="list-style-type: none"> <li>• Identified methods and tools for knowledge modelling</li> </ul>

### 3.4 Phase 2: Data collection and analysis

Data collection and analysis is essential for knowledge model development as the final results will be greatly influenced by the efficiency of data and information. Thus, a questionnaire, semi-structured interviews and further literature reviews have been conducted in this phase to collect enough efficient data and information, after which bar/pie charts and concept/mind mapping have been utilized for data analysis as shown in Table 3-2.

Table 3-2 Key tasks, tools and outputs in phase 2

<b>T2.1. Data collection with questionnaire, semi-structured interview and literature review</b>	
Tools and methods	<ul style="list-style-type: none"> <li>• Questionnaire</li> <li>• Semi-structured interview</li> <li>• Literature review</li> </ul>
Outputs	<ul style="list-style-type: none"> <li>• Designed questionnaire and results</li> <li>• Interview questions and results</li> </ul>
<b>T2.2. Data analysis with bar/pie chart and concept/mind mapping</b>	
Tools and methods	<ul style="list-style-type: none"> <li>• Bar/Pie chart</li> <li>• Concept/Mind mapping</li> </ul>
Outputs	<ul style="list-style-type: none"> <li>• Analysis of the results from questionnaire</li> <li>• Concept/Mind map</li> </ul>

### 3.5 Phase 3: Knowledge model development

Concept mapping and process mapping are used to further analyze the LBW process capabilities in the aircraft industry, based on the concept/mind mapping built in the last phase. An IDEF0 map was built for the LBW structure development to identify the inputs, outputs, controls and mechanics. Then the knowledge can be identified, captured in the form of rules and recommendations and represented with UML. Regular review meetings with both academic supervisors and industrial specialists have been of great benefit to this research as many suggestions and improvements have been gained. The key tasks, tools and outputs in this phase are shown in Table 3-3.

Table 3-3 Key tasks, tools and outputs in phase 3

<b>T3.1. Identify the LBW structure design and process planning considerations</b>	
Tools and methods	<ul style="list-style-type: none"> <li>• Concept map</li> <li>• Process mapping/IDEF0</li> </ul>
Outputs	<ul style="list-style-type: none"> <li>• Inputs, outputs, controls and mechanics of structure design and process planning</li> <li>• Identified and classified structure design and process planning considerations</li> </ul>
<b>T3.2. Capture the knowledge as rules and recommendations</b>	
Tools and methods	<ul style="list-style-type: none"> <li>• Rules and Recommendations</li> </ul>
Outputs	<ul style="list-style-type: none"> <li>• Rules and recommendations based on the classification built in T3.1</li> </ul>
<b>T3.3. Represent the knowledge with UML</b>	
Tools and methods	<ul style="list-style-type: none"> <li>• UML</li> </ul>
Outputs	<ul style="list-style-type: none"> <li>• Presentation</li> </ul>

### 3.6 Phase 4: Validation

The skin-stringer connection of an aircraft's aft fuselage panel is a typical structure in the aircraft industry, and Airbus has proved the suitability of the LBW process for this structure already. So it has been chosen as the case to be studied in this project. The proposed knowledge model is applied to this specific process, and the results have been assessed by industrial experts. Experts' judgements have been gathered during this term and reflected in the final work. With the results of the case study and expert judgements, the developed knowledge model can be validated. The key tasks, tools and outputs in this phase are shown in Table 3-4.

Table 3-4 Key tasks, tools and outputs in phase 4

<b>T4.1. Case study: LBW of fuselage panel of airplane Cxxx</b>	
Tools and methods	<ul style="list-style-type: none"> <li>• Semi-structured interview</li> <li>• Industry survey</li> </ul>
Outputs	<ul style="list-style-type: none"> <li>• Handbook</li> </ul>
<b>T4.2. Expert judgement</b>	
Tools and methods	<ul style="list-style-type: none"> <li>• Structured interview</li> </ul>
Outputs	<ul style="list-style-type: none"> <li>• Comment</li> </ul>

### 3.7 Summary

This chapter has described the research methodology adopted in this project which is divided into 4 phases. Information and data were firstly collected from the questionnaire, semi-structured interviews and literature review, and then analyzed in a bar/pie chart and concept/mind mapping. The design and process planning considerations were identified through an IDEF0 map, captured as rules and recommendations and represented with UML. All these were validated through judgements from industry experts regarding a fuselage panel from a commercial aircraft.



## **4 Identified Methods and Tools for Knowledge Modelling**

### **4.1 Introduction**

This chapter introduces the adopted methods and tools for knowledge modelling in this research, which are identified through literature review and unstructured interviews. Considering the background of investigated company and the research scope, a Knowledge Life Cycle (KLC) developed within a Lean Product and Process Development project and its phases related to this project were identified firstly. Then appropriate methods and tools for each of the selected phases were identified as well as the main tasks in these phases.

### **4.2 Identified Knowledge Life Cycle and Phases**

The selection of a KLC was conducted according to several factors and their influence, such as the advantages of the KLC model and its applicability to the objective company and application. After evaluating the presented KLCs in section 2.2.1, both KLCs from Rodriguez and Al-Ashaab (2007) and Maksimovic et al. (2011) could be adopted here for their completeness and the advantages of the model. However, the latter is more applicable to the company under investigation because this company has over 25 years of experience in aircraft manufacturing and has used the concept of lean manufacturing for a number of years. The company is looking for a KLC model that could contribute to the continual improvement of its experience and technology. The KLC from Maksimovic et al. (2011) developed within a Lean Product and Process Development project, which was established for the continual improvement of product based on the continual improvement of knowledge. This is completely in line with the requirements of the company, thus this KLC is adopted in this project. The selected KLC model is illustrated in Figure 4-1.

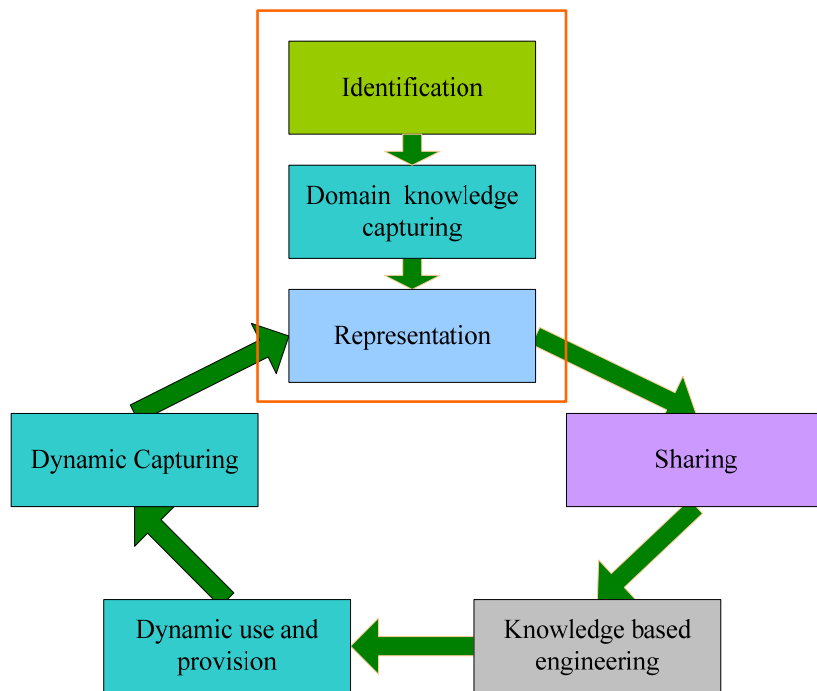


Figure 4-1 Schematic diagram of Knowledge Life Cycle (Maksimovic et al., 2011)

Considering the project scope listed in section 1.4, the aim and objectives introduced in section 1.6 and the literature review of knowledge modelling in section 2.2, the adopted phases of the selected KLC in this project are knowledge identification, capture and representation. A brief description for each phase is presented in Table 4-1 to establish the main task of each of these phases. Taking the knowledge identification phase as an example, the considerations for LBW structure design and process planning should be identified.

Table 4-1 Description of adopted phases

KLC stages	Brief description
<b>1. Identification</b>	<ul style="list-style-type: none"> <li>Identify the considerations for the LBW structure design and process planning.</li> </ul>
<b>2. Domain knowledge capture</b>	<ul style="list-style-type: none"> <li>Capture knowledge about structure design and process planning in the form of rules and recommendations.</li> </ul>
<b>3. Representation</b>	<ul style="list-style-type: none"> <li>Represent the captured knowledge with UML.</li> </ul>

### **4.3 Adopted Methods and Tools**

The adopted methods and tools for knowledge capture and representation of the LBW process in the aircraft industry were listed in Table 3-3 and introduced in section 3.4. According to the collected information from the literature and unstructured interviews with engineers in COMAC, a further description of the adopted methods and tools has been presented as follows.

#### **Stage 1: Identification- IDEF0 and Concept Mapping**

Before identifying the main considerations, a clear understanding of the LBW structure development procedure should first be gained. According to the literature review, IDEF0 is an advanced method for process knowledge modelling. Thus, it is selected to model the LBW component development procedure. Based on this approach, the inputs, outputs, controls and mechanics of the LBW structure development could be identified, and a clear understanding of this process gained. Considering the collected information from the questionnaire and semi-structured interviews, the main considerations for structure design and process planning can be identified. According to the initial literature review, there are many parameters and factors that should be considered during the procedure. It is better to categorise them into more manageable aspects that are easy to understand and manipulate. So the engineers and designers can understand this knowledge more easily. As concept mapping is advanced in knowledge classification and designing complex structure, this method is also selected for identifying the main considerations.

#### **Stage 2: Domain Knowledge Capture- Rules and Recommendations**

Rules and recommendations are the favourites of engineers in the aircraft industry as the structure design and process planning are always followed by guidelines constructed with rules and recommendations. Taking the riveting process as an example, there are many rules and recommendations for this process, such as the recommended diameter of riveting holes for different structures and the minimum clearance between two closest riveting holes. By following these rules and recommendations, designers and engineers can avoid many unnecessary mistakes in the design and process planning stage and

improve the feasibility of the design and process. This makes the job much easier and contributes to a significant cost reduction. The designers and engineers wish that there were also such rules for the structure design and process planning for the LBW process. Furthermore, rules and recommendations can be recognized by computers and so are able to be applied to knowledge or expert systems conveniently. Thus, this method is used in this project to capture the knowledge about structure design and process planning. The rules are used to express the restrictions or general trends and the recommendations to express the suggested techniques or solutions.

### **Stage 3: Representation- Unified Modelling Language**

The knowledge will be used for sharing or training after knowledge modelling. So this knowledge should be represented in a way that is easy to understand. Unified Modelling Language (UML) is a standardized visual diagramming language, which is used for representing knowledge schematically. It is able to build several different kinds of UML models, such as the class diagram and activity diagram, and make the knowledge easy to understand. Thus, it is selected for knowledge representation in this research.

## **4.4 Summary**

Based on the literature review, a KLC model developed within a Lean Product and Process Development project was first identified, which could facilitate the continual improvement of knowledge. Considering the research scope, only the first three phases of this KLC model were adopted in this research: identification, domain knowledge capture and representation. Then tasks for each of the phases were defined, based on which methods and tools were adopted for these phases, namely IDEF0 and concept mapping for knowledge identification; rules and recommendations for domain knowledge capturing and UML for knowledge representation. All these methods and tools contribute to the knowledge model development in chapter 6.

## **5 Data Collection and Analysis**

### **5.1 Introduction**

In order to obtain information about the LBW process in the aircraft industry, a questionnaire, semi-structured interviews and a further literature review have been conducted in this phase. The collected information from the questionnaire is firstly analyzed into bar/pie charts, and then classified as design and process factors of the LBW process together with those information obtained through interviews and literature. The results from the questionnaire are recorded in Appendix B while the results of the semi-structured interviews and further literature review are recorded in Appendix C. The quality of the interviewees as well as the collected design factors and process factors will be demonstrated and analysed in this chapter.

### **5.2 Data Collection**

A closed questionnaire was implemented by the author in this phase based on the general findings from the initial literature review and unstructured interviews, aiming to collect information about the LBW process in the aircraft industry. The questionnaire and results were sent by email, based on which the semi-structured interviews were conducted to obtain more detailed information. Most of the semi-structured interviews were conducted through Web conferencing while two of them were conducted by telephone with two different manufacturing engineers.

#### **5.2.1 Questionnaire Development**

The questionnaire itself is divided into three sections and contains 20 questions. The first section contains four questions for general information about the interviewees, which are designed to verify the quality of the interviewees. Twelve questions are included in the second section to collect information about LBW in the aircraft industry from four different fields: design, manufacturing, fixture and research. Four questions are designed in the third section to find a general attitude on knowledge modelling of the LBW process in the aircraft industry. Because four different aspects are referred to in the questionnaire, the selected

interviewees should cover all these fields and have enough experience on at least one or two of them. As the interviewees are from China, the questionnaire was designed in two versions, English and Chinese. The questionnaire in English is shown in appendix A, while the Chinese version is not attached.

Figure 5-1 shows two examples of the designed questions in the questionnaire, which aim to identify the advantages of the LBW process in the aircraft industry and structure design considerations, respectively. According to these questions, the focus of engineers, designers and researchers can be identified and a general result achieved.

L1. From your experience, what are the greatest advantages of LBW process within aircraft industry, comparing with traditional joining processes? (You can choose four options at most)

A. Weight saving	B. Structure complexity	C. Material consumption
D. Quality improvement	E. Production rate	F. Process Stability
G. Corrosion resistance	H. Cost saving	I. Other
J. Not sure		

**Other:** \_\_\_\_\_

L7. What should be taken into account when designing the LBW joints (skin-stringer)? (You can choose as many options as you wish)

A. Weldability of material	B. Capability of welding equipment
C. Skin geometry	D. Skin manufacturing method
E. Stringer geometry	F. Stringer manufacturing method
G. Tolerance	H. Dimension
I. Other	J. Not sure

**Other:** \_\_\_\_\_

Figure 5-1 Example of designed questions in the questionnaire

Only two questions from the questionnaire have been introduced briefly in this section. The complete questionnaire is presented in Appendix A; the results were collected in an Excel document, analyzed by bar/pie chart and are

recorded in Appendix B. These results have indicated the direction for further investigations. For example, if the results of questionnaire illustrate that tolerance is an important factor to as-welded profile, further and detailed question will be designed for the semi-structured interviews to collect detailed information about tolerance.

### 5.2.2 Semi-structured Interview

Based on the results of the closed questionnaire, a series of semi-structured interviews were conducted to obtain further information about the structure design and process planning, such as the exact geometry and tolerance. The engineers and specialists interviewed in this stage were from COMAC, including three structure designers, two manufacturing engineers, two fixture/tooling designers and four LBW process researchers as shown in Table 5-1. The questions and results of the interviews are recorded in Appendix C.

Table 5-1 List of the interviewed engineers and specialists

Role	Number	Experience
Aircraft structure Designer	3	3-5 years
Manufacturing Engineer	2	over 10 years
Fixture/tooling Designer	2	3-5 years
LBW process researcher	4	3-5 years

Seventeen questions were designed for the semi-structured interviews about the dimension, tolerance and other detailed information, covering fuselage panel structure design, LBW process planning and fixture design in three domains. For example, the question “For chemical milled skin, what tolerance is usually given in the design stage? Is there any rule?” was designed to investigate the design tolerance of chemical milled skins whilst question “For stringers, what tolerance is usually given in the design stage? Is there any rule?” was asked to elicit the design tolerance of a stringer. These two together contribute to the fit-up tolerance which will influence the weld quality. Some rules and recommendations can be defined or other solutions could be taken in advance to

avoid or reduce the influence of fit-up tolerance based on the results of these questions, which will be discussed in chapter 6.

### **5.3 Data Analysis**

It is widely accepted in the manufacturing industry that the data and information of each production can be divided into three domains: product, process and resource. The product domain contains data and information produced in the design stage, including the design models and technique requirements, whilst the process and resource domains contain data produced in the process planning stage. This view is also defined in the structure of ISO 10303-214(ISO/TC184/SC4) and other standards. It is obvious that the LBW process in the aircraft industry should follow this basic principle.

In this thesis, product information includes design factors induced in the design stage whilst process and resource information means process factors induced in the process planning stage. The LBW process capabilities are greatly influenced by these factors. The data and information collected in section 5.2 will be analyzed and categorized as design factors and process factors in this section. Furthermore, the quality of interviewees will be analysed to verify firstly how reliable the results could be.

#### **5.3.1 Quality of Interviewees**

The questions in the first section of the questionnaire are designed to verify the quality of interviewees. The results are analyzed and illustrated in Figure 5-2. Sixteen interviewees responded to this questionnaire, from three different organizations: an aircraft design institute, an aircraft manufacturing company and a university in China. 50% of them are design engineers (four product designers and four fixture designers), while others are manufacturing engineers, research fellows of LBW, covering all the fields that the questionnaire refers to. Over 60% of them have three to ten years' experience either in process planning, aircraft structure design or LBW. Only one interviewee has less than one year's experience. As LBW in the aircraft industry has only about ten years' history, the interviewees' experience makes them reliable for this questionnaire. Accordingly,



the results of this questionnaire should be relatively reliable and could be referenced while developing the knowledge model.

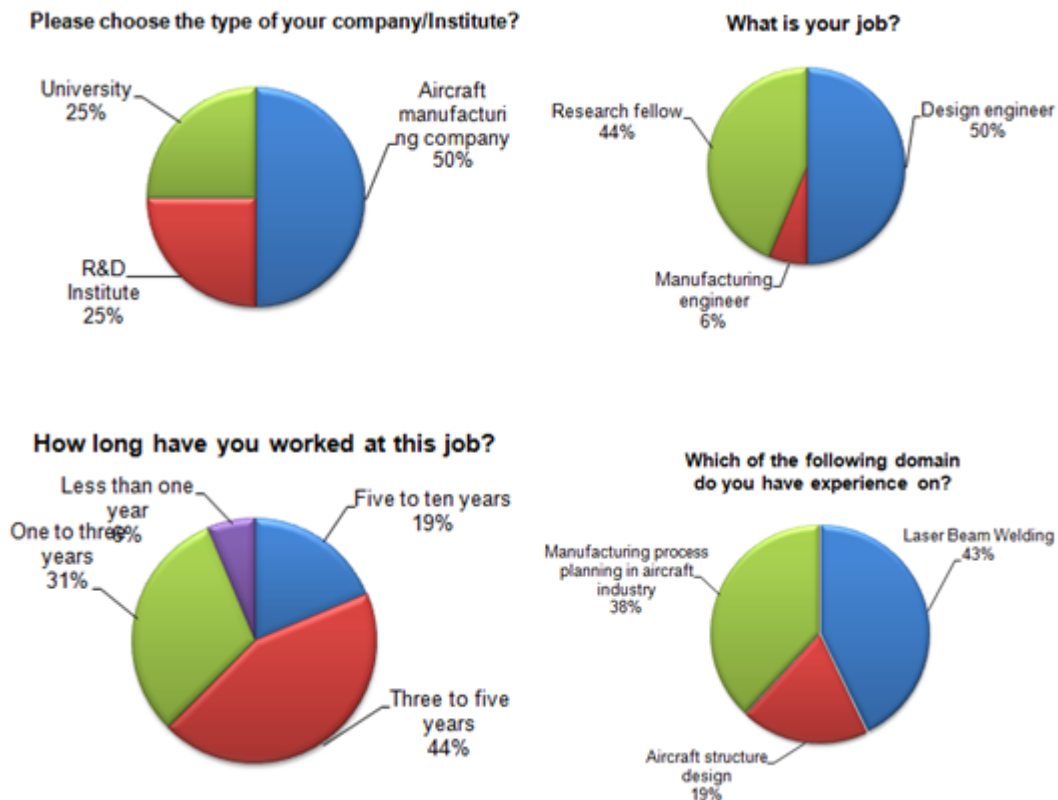


Figure 5-2 Results of general information on interviewees

### 5.3.2 Design Factors

The first issue to be considered in structure design is “tolerance” according to the questionnaire, as 94% interviewees have chosen this option. “Weldability of material”, “skin geometry” and “stringer geometry” is chosen by 75% of interviewees or more. Only 6% of interviewees have chosen “skin manufacturing method” and “stringer manufacturing method”. Tolerance is always a crucial issue in the aircraft industry, not only for LBW. This results from the unique characteristics of aircraft structure. Because most stringers are standard profile and skins are fabricated with a mature process, such as stretching or chemical milling, the manufacturing methods of these parts seem to attract little attention. The complete answers to the question “What should be taken into account when designing the LBW joints (skin-stringer)?” are illustrated in Figure 5-3. The labels on the vertical axis are options defined in the question, while the number on the horizontal axis stands for the number of interviewees. Based on this result and

after combining some similar options, such as combining the stringer geometry and skin geometry as geometry, the (skin-stringer) joint structure design factors are categorized as material and structure, i.e. two aspects, which are shown in Figure 5-4.

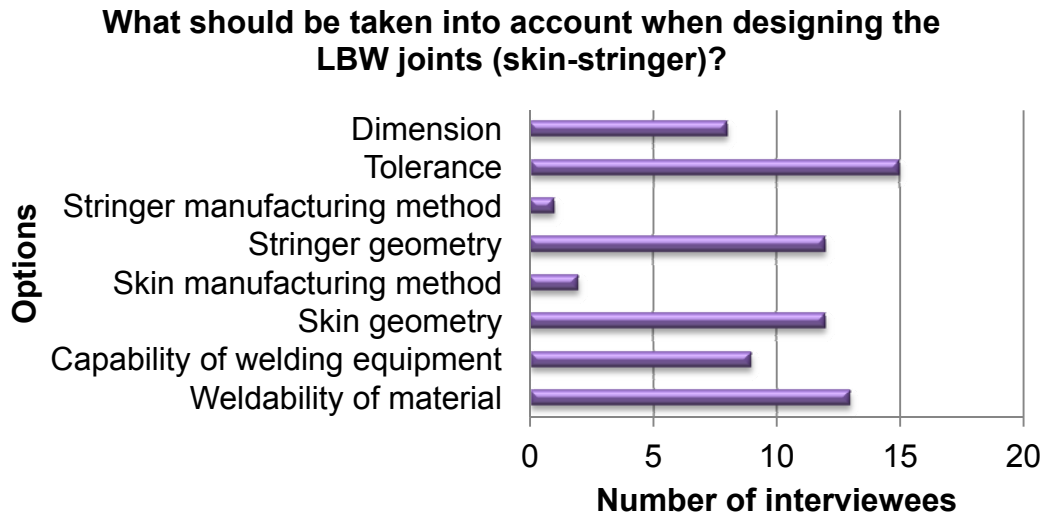


Figure 5-3 Design considerations (skin-stringer)

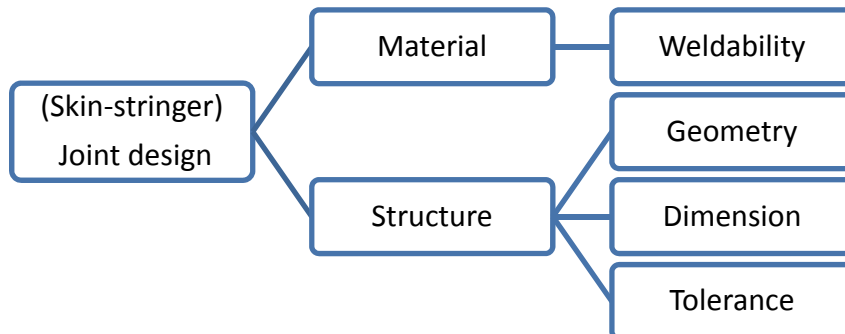


Figure 5-4 Category of skin-stringer joint design factors

#### 1) Material:

It can be verified from both the literature and the questionnaire that many aluminium alloys in the aircraft industry have been tested and approved to be weldable and some of them with good weldability, including most 6xxx series aluminium alloys and the latest Al-Li alloys. Some of them, such as 6056, 6013 and 6156 have already been used in certain commercial aircraft by Airbus. Table 5-2 lists the partial composition of alloying elements of some aluminium alloys with good weldability according to Kaufman (2004). A standard 2024 alloy was

also listed in this table for comparison. The Cu% (the content of Cu within the alloy) and Mg% of the weldable aluminium alloys is lower than that of the standard 2024 aluminium alloy. The weldability of material is mainly affected by reflectivity, absorptivity & thermal conductivity of the material as well as the process parameters (American Welding Society (AWS), 2010), because all these aspects will affect the heat balance or heat cycle during the welding procedure.

Table 5-2 Partial alloying composition of some materials with good weldability  
(Kaufman, 2004)

Alloy	Mg	Mn	Li	Si	Cu	Zn	Cr
<b>2024</b>	1.2-1.8	0.3-0.9	-	<0.5	3.8-4.9	<0.25	<=0.10
<b>6013</b>	0.8-1.2	0.2-0.8	-	0.6-1.0	0.6-1.1	<=0.25	<=0.10
<b>6056</b>	0.6-1.2	0.4-1.0	-	0.7-1.3	0.5-1.1	0.1-0.7	<=0.25
<b>6061</b>	0.8-1.2	<=0.15	-	0.4-0.8	0.15-0.4	<=0.25	0.04-0.35
<b>6156</b>	0.6-1.2	0.4-1.0	-	0.7-1.3	0.5-1.1	-	-
<b>2198</b>	0.25-0.80	<=0.50	0.8-1.1	<=0.08	2.90-3.50	<=0.35	<=0.05

## 2) Structure:

The joint structures for the aircraft fuselage shell include skin-skin, skin-stringer, skin-clip and frame-X connections, which could be defined as butt joint, T butt joint and tap joint. However, not all of these joints have been applied with the LBW process yet, because some of the current structure is not suitable for LBW.

The verified structure by Airbus was skin-stringer/skin-clip T butt joint after modifying the stringer and clip geometry as well as the seat rail butt joint. The potential utilization may include skin-skin butt joint and frame-X joint (skin, stringer or clip, depending on the structure). Figure 5-5 illustrates a general comparison between the traditional structure for riveting and the structure for LBW. According to question "Which of the following joint types will you choose for LBW in the aircraft industry?" in the questionnaire, the preferred skin-stringer joint structures were identified by the designers and engineers. Some of the structures are shown in Figure 5-6.

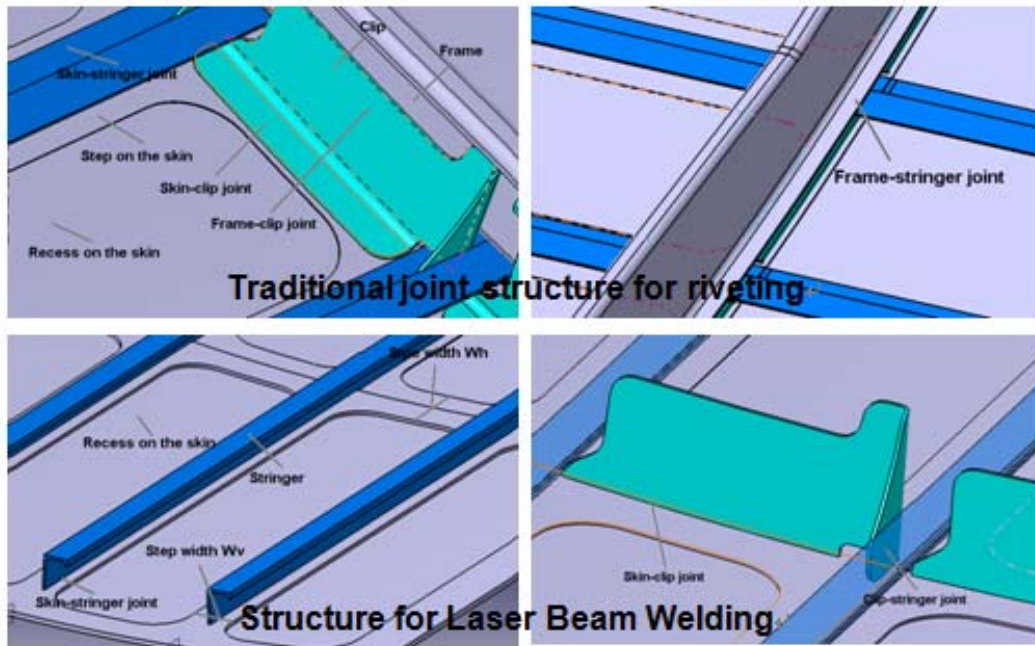


Figure 5-5 Comparison between riveting structure and welding structure

As illustrated in Figure 5-6, the joint structure shown in (1) is built with formed stringer and chemical milled skin with various thicknesses whilst the structure in (2) is built with extruded stringer and skin with uniform thickness, which is mostly stretched skin. Structure (3) illustrates further simplified stringer geometry in order to reduce weight, and structure (4) presents the geometry for the clip. The application of the structure in (3) needs more investigation and analysis to determine its longitudinal stability.

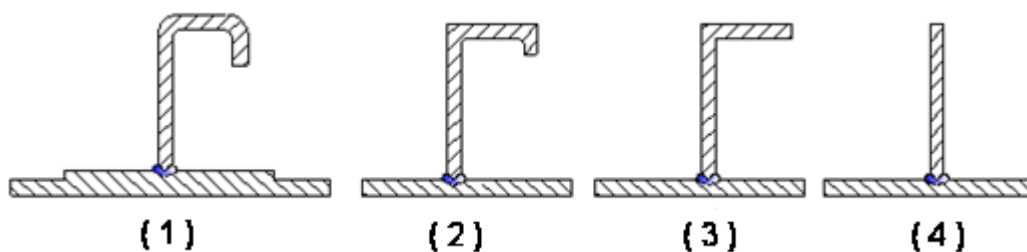


Figure 5-6 Partial preferred joint structure for Laser Beam Welding

According to the information collected from the semi-structured interviews, structure (2) within Figure 5-6 would be adopted, which is shown in Figure 5-7 in more detail. The dimension and tolerance of the stringer is referenced to the Aluminium Association (AA) Material Specification, as most of the stringers are

standard extruded profiles for cost reduction. A typical skin thickness is 1.8 mm following the rule of thumb that the common range of skin thickness for a low fuselage panel is between 1.4 mm and 2.2 mm. Because the strap on the stringer or clip is eliminated for weight reduction, the step width on the skin can also be reduced in condition that the skin is chemical milled with various thickness, i.e. commonly about 20 mm depending on the chosen profile. Figure 5-8 illustrates a comparison between skin for riveting and skin for LBW about the step width, namely  $W_h$  in the horizontal direction and  $W_v$  in the vertical direction.

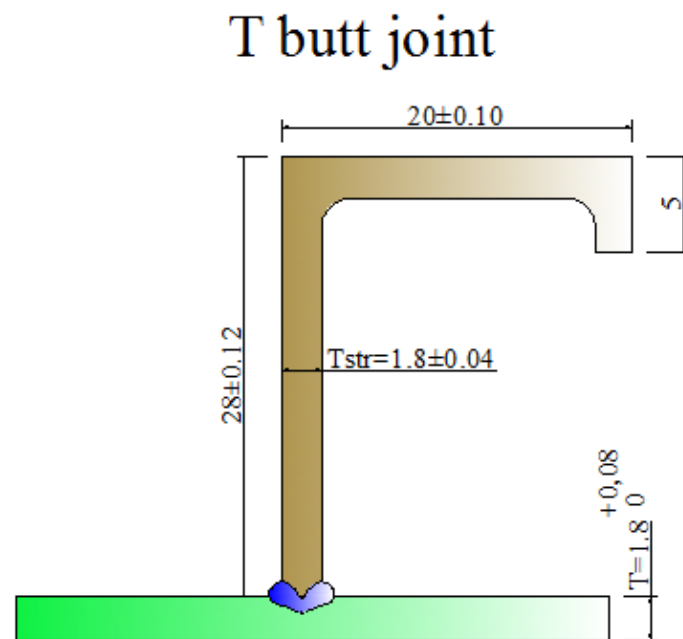


Figure 5-7 Skin-stringer joint structure for Laser Beam Welding

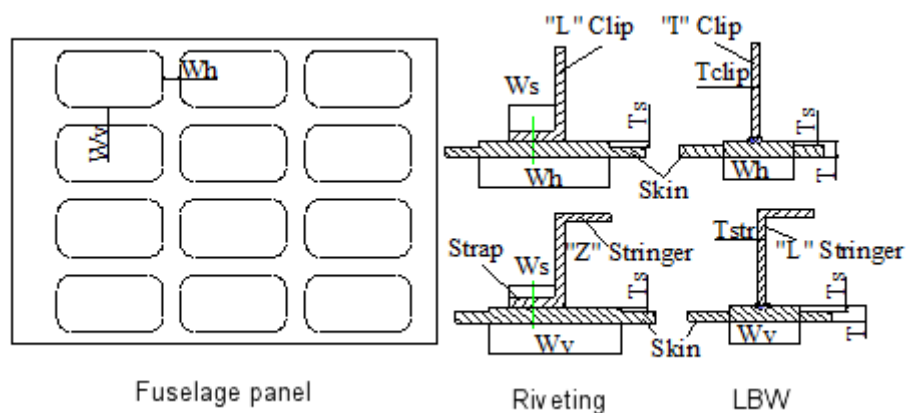


Figure 5-8 A comparison of step width between the skin for riveting and the skin for Laser Beam Welding

### 5.3.3 Process Factors

According to the question “What should be taken into account when planning the LBW process?”, 75% to 94% of the interviewees considered “Design requirement”, “Welding equipment” and “Fixture” as process planning factors, while 50% to 63% of them chose process parameters such as “focal position”, “shielding gas”, “laser power”, “welding speed” and “filler metal”. Furthermore, 44% of interviewees suggested other aspects, such as “pre-welding preparation”, “post-welding treatment” and “the design of the welding head” as this will influence the feeding method of the filler. The complete answers are illustrated in Figure 5-9 and further categorized in Figure 5-10. The design requirements appear to attract most attention; however, as the design requirements have already been discussed in the design factors in section 5.3.2, this aspect will not, therefore, be discussed in the process factors another time.

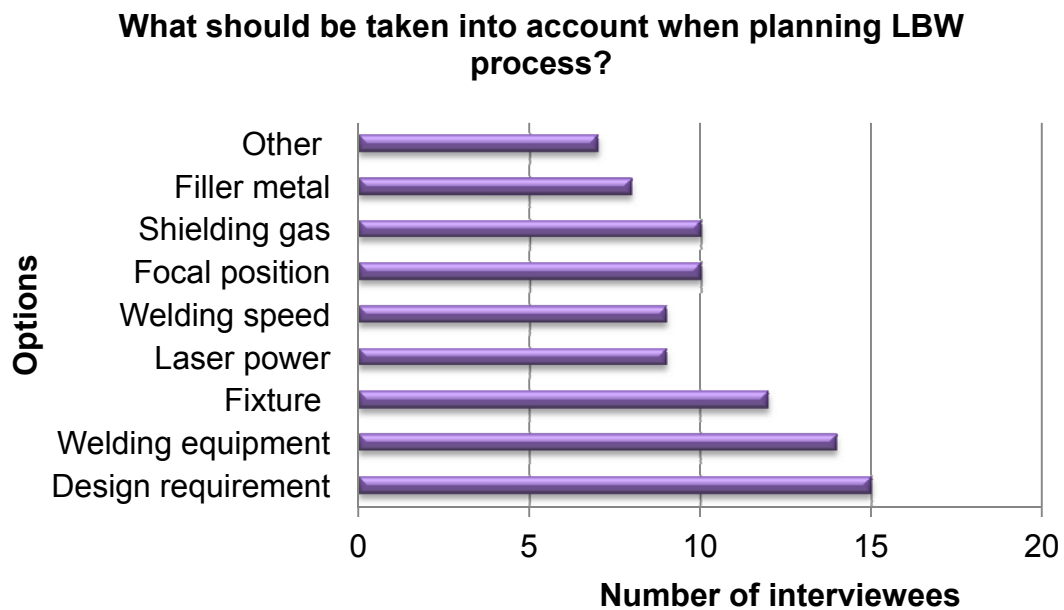


Figure 5-9 Process planning considerations

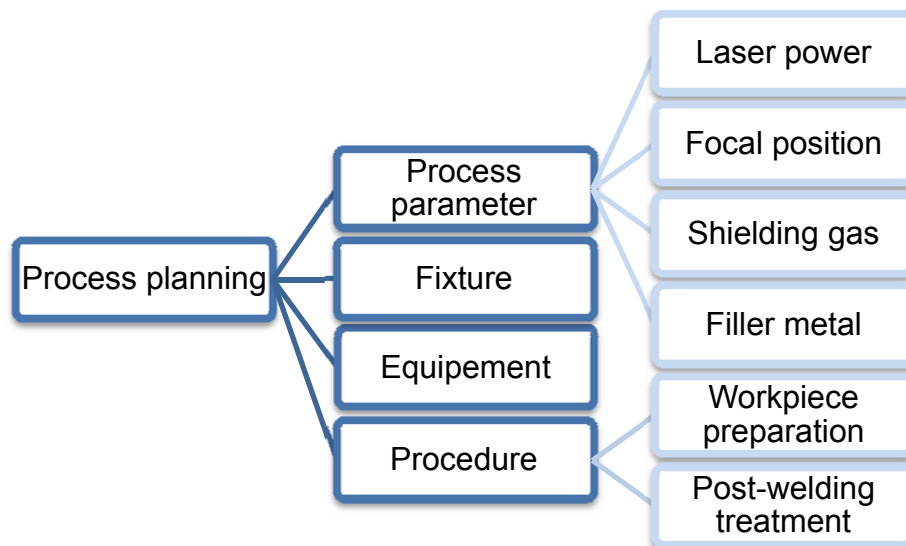


Figure 5-10 Category of process factors

### 1) Procedure

According to the results of the question “Which are the essential stages for the LBW process”, the LBW procedure can be presented as shown in Figure 5-11. Workpiece preparation includes eliminating contaminants, such as moisture, oil and dust, and pre-welding treatment when necessary. Contaminant elimination is essential as contaminants such as moisture will cause hydrogen pores and influence the weld strength. Pre-welding treatment such as pre-heating is not necessary as the workpiece in the aircraft industry is usually thin aluminium sheet of less than 4 mm and the laser power today is high enough. Locating and clamping the workpiece accurately and tightly is necessary as the weld/beam alignment will influence the weld quality. Inspection is always necessary to confirm the weld quality whilst post-welding treatment only needs to be conducted when necessary.

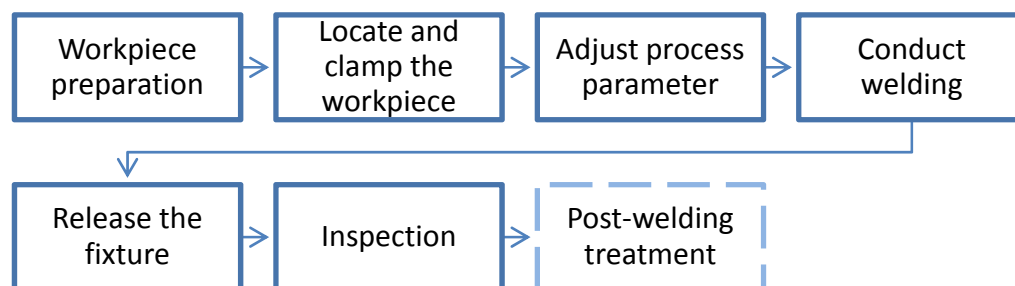


Figure 5-11 Laser Beam Welding procedure from questionnaire

## 2) Process Parameters

High quality laser welds are obtained only after the optimization of key process parameters. The initial results of process parameters from the questionnaire are recorded in the Appendix B question “From your experience, what are the most important factors of LBW process capabilities within aircraft industry?” After amalgamating the results from the semi-structured interviews and further literature, the factors are further categorized as illustrated in Figure 5-12, including laser power, focal position, protection gas, joint preparation, filler metal and welding speed.

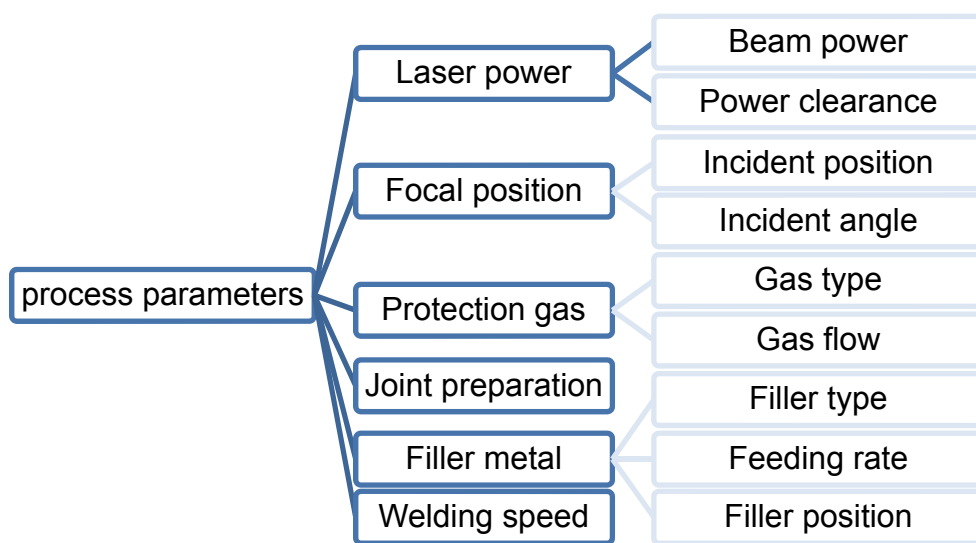


Figure 5-12 Laser Beam Welding process parameters

Laser power is an independent factor that can be adjusted to achieve better performance; the weld width and depth increase with beam power. The high power density has a strong influence on the microstructure as well as the properties of the welded joint. Focal position related variables include incident position and incident angle. These are related to the weldability of the workpiece thickness and should be set where the maximum penetration depths or best process tolerances are produced. The utilization of protection gas could reduce oxidation, pores and obtain a better root surface quality. Using different shielding gas feeding speeds can optimize the process with regard to seam formation. The surface condition may influence the energy absorption of laser beams as well as the threshold power density for keyhole welding. Filler metal related variables include filler type, feeding speed and filler position. The use of filler metal can promote process stability, reduce porosity and lower the sensitivity to joint gaps.



It can also improve weld strength through compensating vaporized elements while welding. Welding speed is another variable that influences the weld width and depth and so influences the tensile strength of the welds. 3 m/min - 8 m/min is often used in the industry. Too low speed is not preferred as it is possible to cause undercut and fully penetration of skin. Too high speed is also not liked because it is possible to cause an incomplete welding. Both of them will cause joint strength reduction.

### 3) Fixture Design

According to question “What should be considered for fixture design which is used for fabricating aircraft fuselage panel using LBW process?” in the semi-structured interviews, the initial considerations of fixture design can be identified. The fuselage panel welding fixture can be divided into two parts. One is for skin location and clamping, and the other for stringer location and clamping. The skin fixture should provide accurate location of the skin as well as thermal uniformity to prevent deformation. Three holes on the skin can complete the location of the skin, e.g. holes H1, H2 and H3 as shown in Figure 5-13. H1 can restrict X1, Y, Z1; H2 restricts X2, Z2; and H3 restricts Z3. These three holes together achieve the 3-2-1 location method, the schematic diagram of which is shown in Figure 5-14.

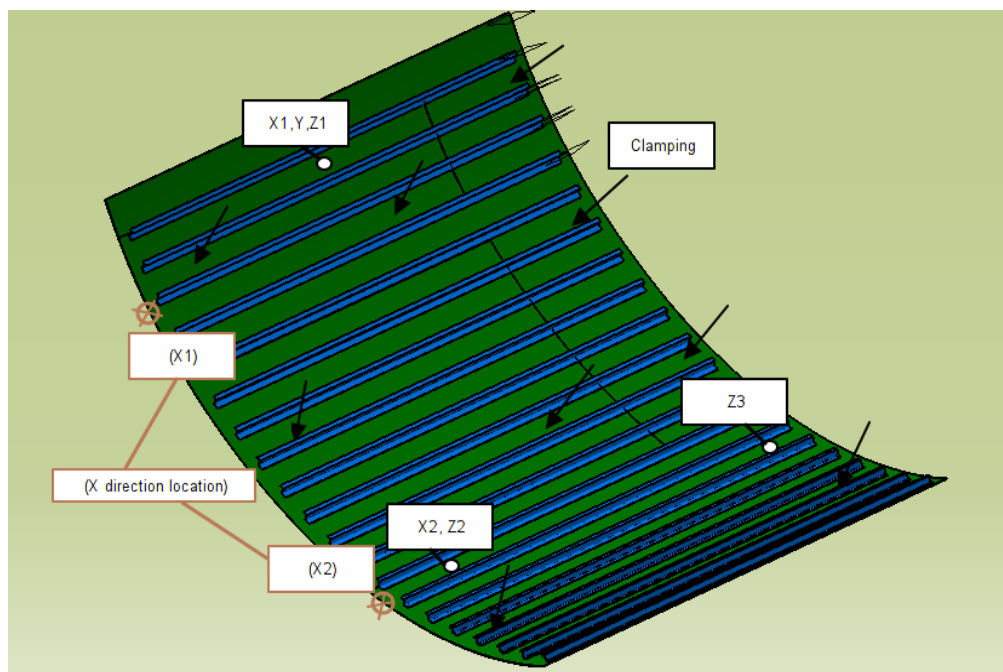


Figure 5-13 Schematic diagram of skin location and clamping

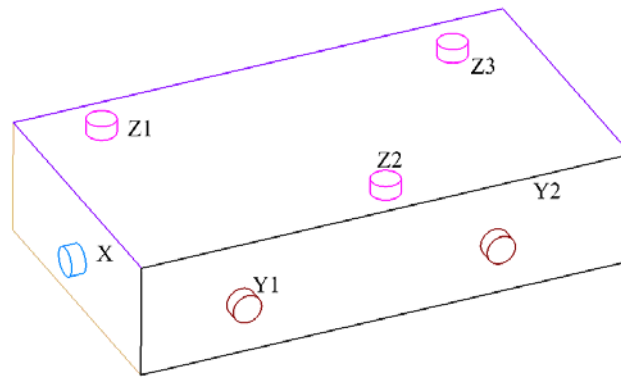


Figure 5-14 Schematic diagram of 3-2-1 location method

The schematic diagram of stringer location is illustrated in Figure 5-15. The side plane A, C of the stringer and the inside surface of the skin are chosen as location planes. For these three planes, plane A can be simplified as points Y1, Y2 and Y3; the skin surface can be simplified as points Z1 and Z2 as the contact area is thin and long, and looks like a line; plane C is just simplified as point X, as the plane is so small compared to the whole stringer. All these points construct the complete location system and restrict the six degrees of freedom.

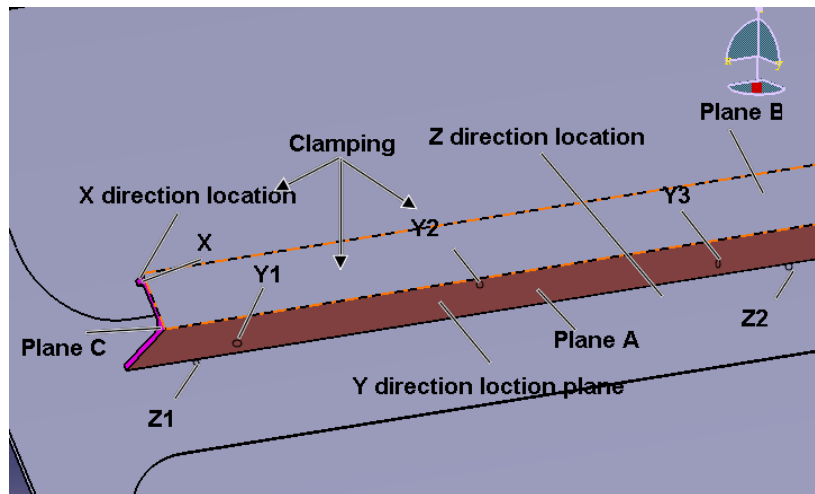


Figure 5-15 Schematic diagram of stringer location and clamping

As the skin is thin and its size usually exceeds 2 m x 1 m, it is better to clamp it on multiple points to prevent natural deformation, thus a vacuum clamp fixture is preferred by the engineers. To ensure the accessibility of the laser beam, a guiding system combined with the working head is preferred. Because in this construction, the guiding system move with the laser beam simultaneously, and has no risk to interrupt the laser beam any more.

#### 4) Process Control

The initial results for process control methods from the questionnaire are recorded in Appendix B. After the semi-structured interviews and investigating several manufacturing process specifications in the aircraft industry from Airbus, Boeing and COMAC, Process Specification is considered to be the most important method for process control. This is because it is found that material control, facility control, technique requirement, work instruction, quality control etc are all contained in the Process Specification. Furthermore, it is stated in CS 25.605 (Certification Specifications for Large Aeroplanes CS-25) that if a fabrication process (such as spot welding) requires close control to reach this objective, the process must be performed under an approved Process Specification. This also proves that Process Specification is an essential vehicle to make the process stable.

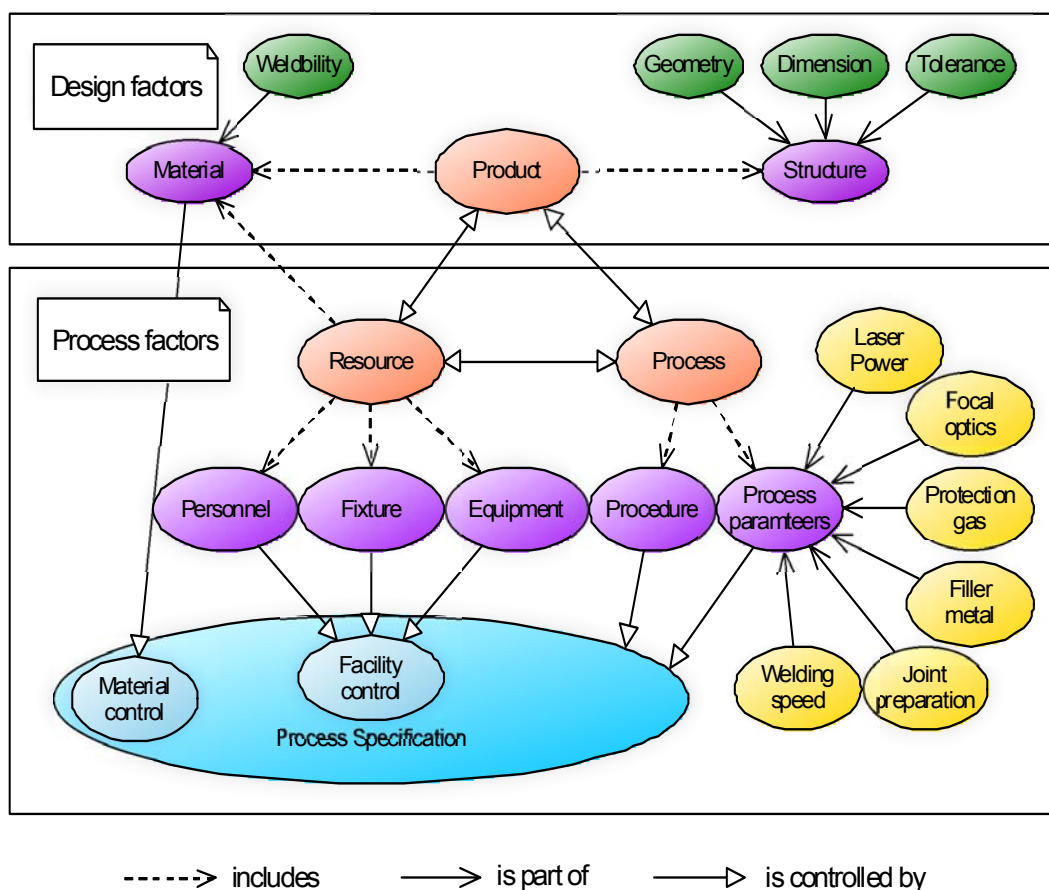


Figure 5-16 Concept map of design and process factors for Laser Beam Welding

## **5.4 Summary**

Based on the collected information from the questionnaire, semi-structured interviews and literature review, all the LBW process-related information is classified as design factors and process factors, i.e. two aspects. Furthermore, the design factors are further categorized as material and structure two aspects while the process factors are categorised as procedure, process parameter, fixture design and process control, i.e. four aspects. A concept map including all of this information has been built to show the inter-relationships of these aspects, as illustrated in Figure 5-16. Each aspect is described and analysed, which provides a foundation for knowledge model development in chapter 6.

## **6 Knowledge Model Development**

### **6.1 Introduction**

A knowledge model for the LBW process in the aircraft industry is developed in this chapter, based on the identified methods and tools in chapter 4 and collected data and information in chapter 5. This chapter introduces the knowledge model development procedure, including identifying the structure design and process planning considerations for LBW, capturing them as rules and representations and representing the captured knowledge, respectively.

### **6.2 Identified Laser Beam Welding Considerations**

In order to identify the LBW structure design and process planning considerations, an analysis of the whole LBW component development procedure was conducted in this section through process mapping with IDEF0. Because the inputs, outputs, controls and mechanics of this procedure were all made clear through this approach, it is easy to address the design and process factors to the right stage of the procedure as considerations. Based on this, the considerations were further classified and described.

#### **6.2.1 Laser Beam Welding Component Development Procedure**

The top-level route map of LBW component development procedure in the aircraft industry is illustrated in Figure 6-1. The whole procedure was broken down into four key stages before obtaining the final product. The design and process planning is guided and assessed by certain rules and recommendations to ensure the design and process quality, while the fixture and component fabrication are assessed by quality control requirements. Although the utilization of Finite Element Analysis (FEA) and Computer Aided Engineering (CAE) tools for static and dynamic structure analysis as well as process simulation are capable of analyzing and predicting the quality of design and planning before real production, they will not be discussed in this thesis as they are deemed to be outside the scope of this project. Rules and

recommendations play an important role in this procedure as it is possible to make the design and process suitable for LBW at the conceptual stage so as to reduce the cost of rework after releasing the design and process.

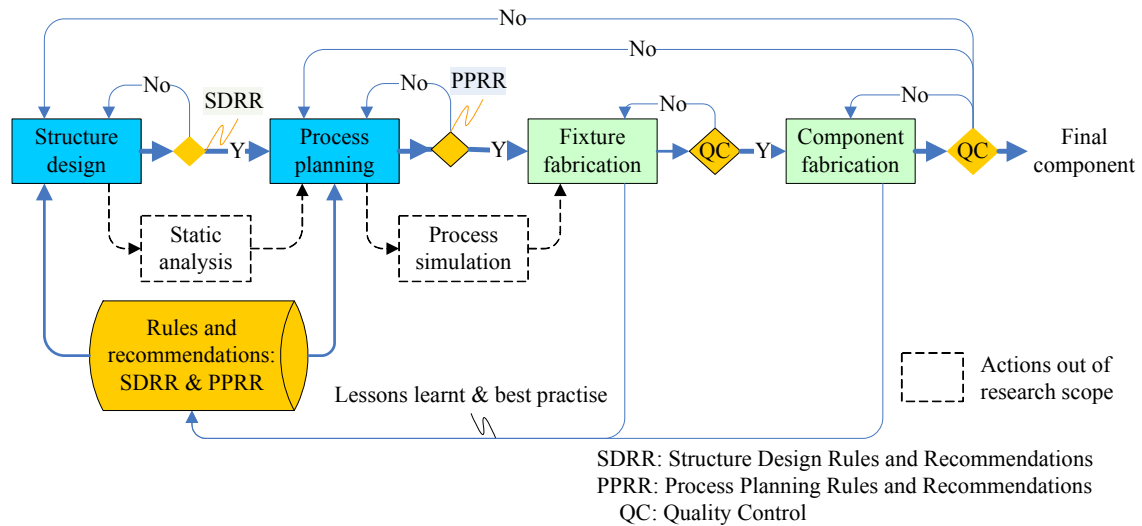


Figure 6-1 Top-level route map of Laser Beam Welding component development

IDEF0 was utilized to build process map of LBW component development procedure as shown in Figure 6-2 for its advantages in process knowledge capture. According to the process map, a clearer understanding of this procedure was obtained as the inputs, outputs, mechanics and controls have been illustrated in the map.

The main inputs of LBW component development include upstream design inputs, including surface geometry, frame plane and stringer axis, and raw materials, whilst the outputs include final product as well as best practice or lessons learnt. The procedure is controlled by geometry restriction, strength requirement, weight saving target, Structure Design Rules and Recommendations (SDRRs) and Process Planning Rules and Recommendations (PPRRs), current manufacturing capability, other regulations of the company, Material Specification and Process Specification. Personnel (including structure designers, process engineers, fixture designers and welding operators), tools (including computers and design software etc), internet/intranet

and facility (fixture fabrication equipment, LBW equipment etc) are the main mechanics of this procedure.

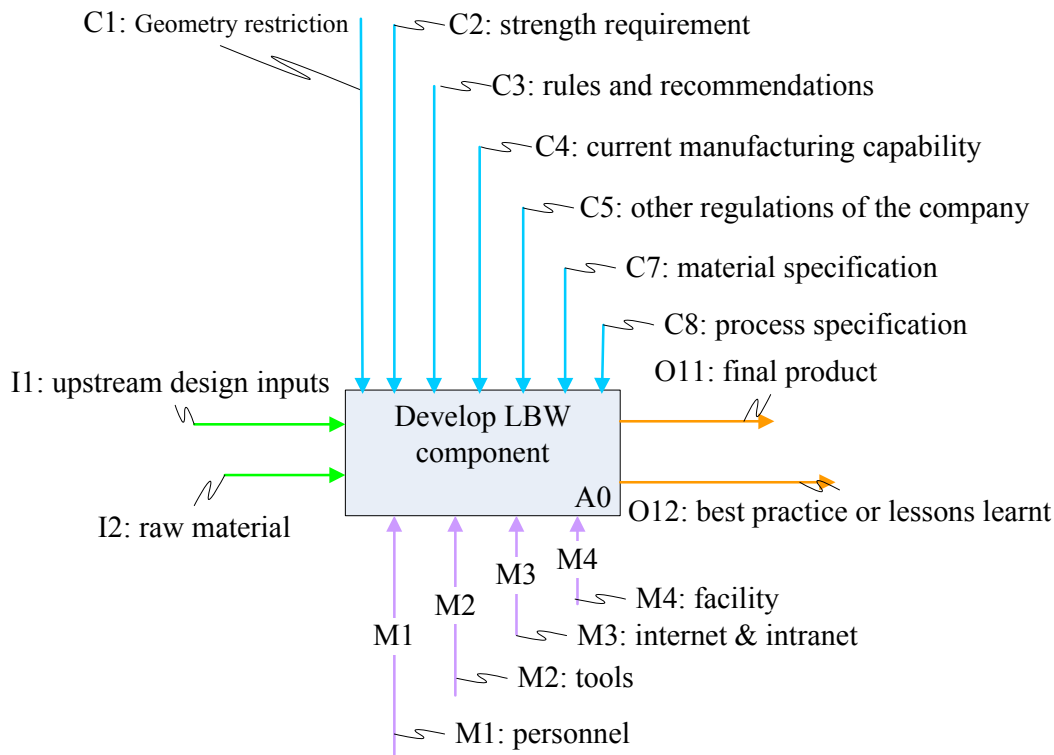


Figure 6-2 A0 map of Laser Beam Welding component development

It is difficult to deal with so many influence factors together, thus, a decomposed IDEF0 A0 map was developed as illustrated in

Figure 6-3. In this figure, the inputs, outputs, controls and mechanics are identified and addressed to the sub-activities of the procedure.

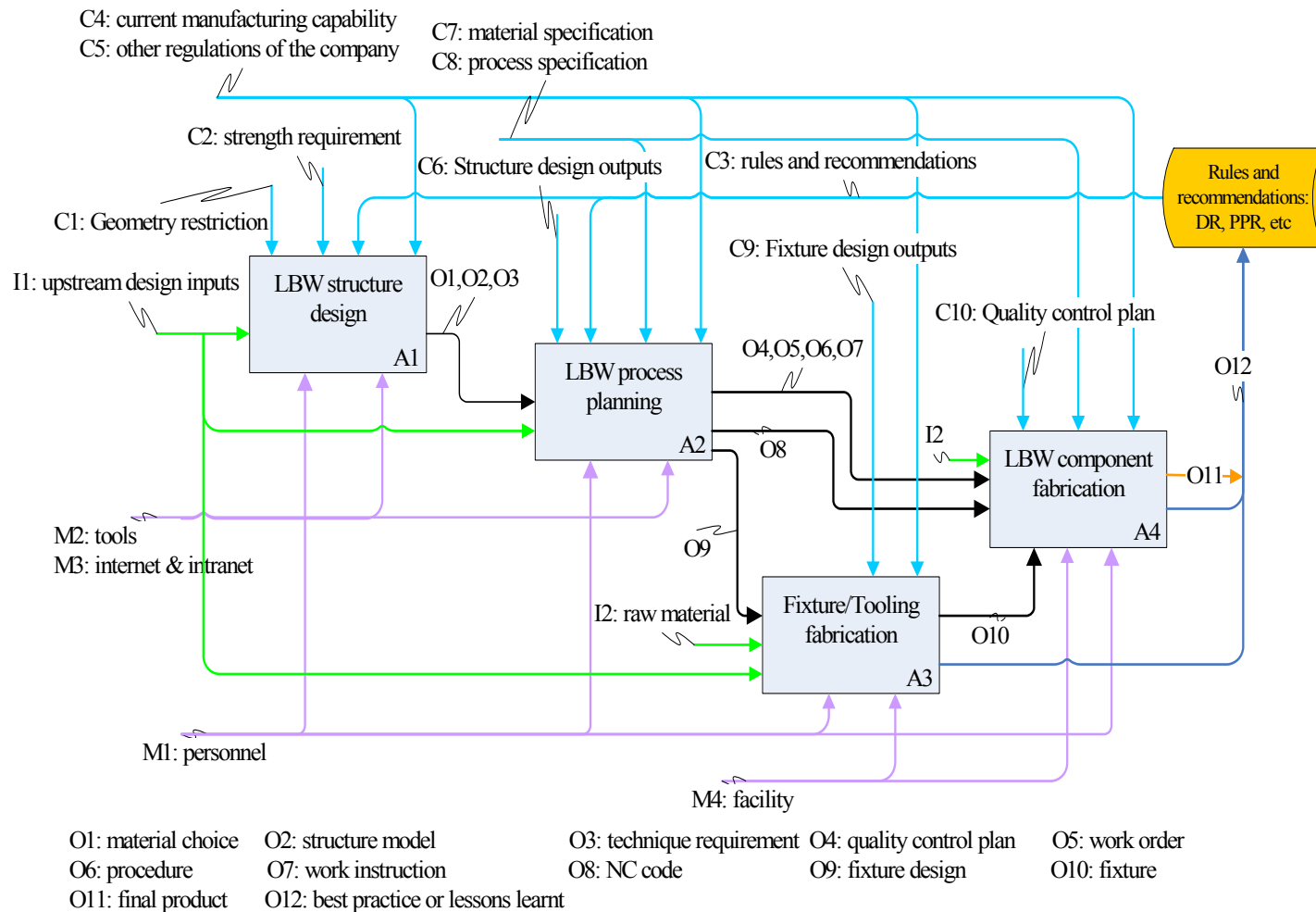


Figure 6-3 Decomposed IDEF0 map for A0: the LBW component development procedure



As fixture/tooling fabrication and LBW component fabrication are both controlled by the outputs of the LBW process planning as illustrated in

Figure 6-3, they are not considered as key stages influencing the LBW process capabilities. This is in line with the statement in chapter 1 that about 60%-85% of the product development cost is committed in the design and planning stages. It is also the structure design and process planning stages that determine LBW process capabilities directly, because most of the LBW process variables are defined and prepared in these two stages. Thus, the identified LBW considerations will be focused on structure design and process planning, which will be described in the following sub-sections in detail. One of the final results, namely best practice or lessons learnt will contribute to the construction of rules and recommendations.

### **6.2.2 Structure Design Considerations**

Based on the decomposed A0 map and collected information for LBW structure design in chapter 4, the A1: LBW structure design action was further decomposed into skin design, stringer design and weld seam design as illustrated in Figure 6-4. The inputs, outputs, controls and mechanics are addressed in the following sections. Additionally, the joint type as well as the structure for skin and stringer should be selected before the design conducted.

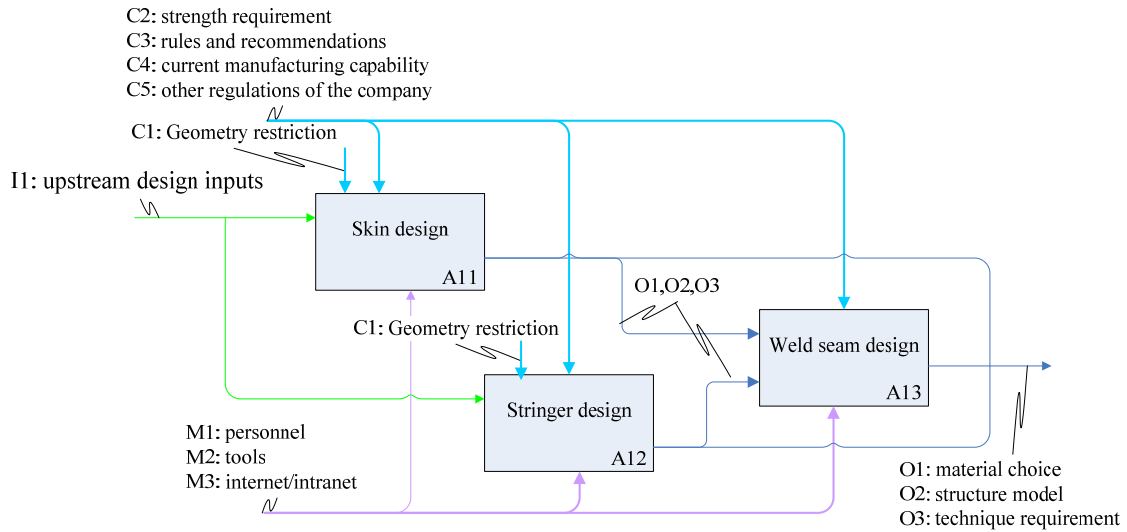


Figure 6-4 Decomposed IDEF0 map for A1: Laser Beam Welding structure design

Based on the above analysis of structure design and the results of the data analysis in section 5.3.2, the considerations are identified and classified into two main aspects, namely material and structure as illustrated in Figure 6-5.

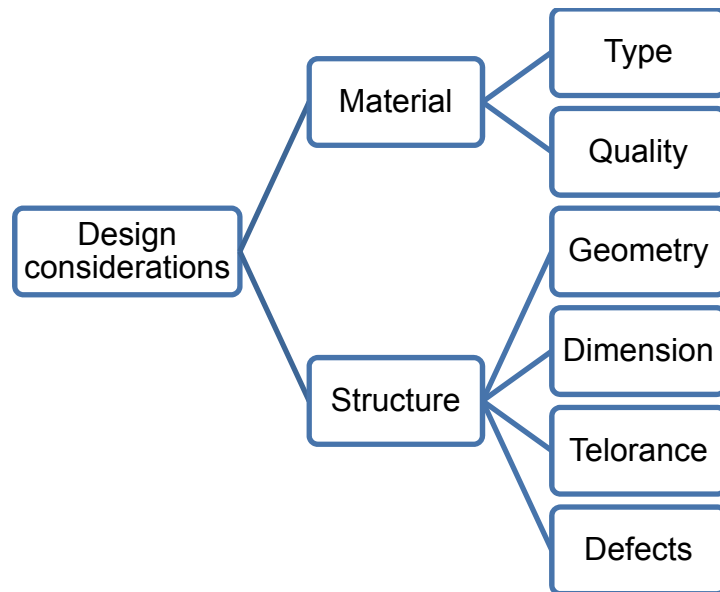


Figure 6-5 Categorization of structure design considerations

## 1) Material

One of the main considerations for LBW structure design is material, including what material to choose and how to ensure the quality of the material. The

weldability of materials is the first influencing factor of material choice, because it determines the weldability of the component directly. Material with better weldability as well as high strength and toughness is preferred. To ensure the quality of material, a Material Specification is specified during this stage to give the process planning a guideline or regulation in order to prepare the materials.

## **2) Structure**

The joint structure should adequately fulfil its service requirements, and the configuration and size should be practical for LBW. It is better designed with minimum influence to the welding operation and at low stress position. The dimension of the skin is limited by the LBW equipment and the process margin. If there is no special requirement, the standard “L” extrusion profile with simple section geometry is preferred and a profile structure with various thicknesses should be avoided.

For any developed aircraft, it is necessary to demonstrate that safety and airworthiness will be given throughout the whole lifetime of the structure. Thus, proper technique requirements should be established, the most important one is Process Specification. Tolerance and weld defects criteria should also be established so that the welding results can be assessed. However, the requirements should also be practical for the current LBW process capabilities. High technique requirements will not provide significant extra safety but will make the process uneconomic.

### **6.2.3 Process Planning Considerations**

Figure 6-6 illustrates the decomposed IDEF0 map for A2: LBW process planning, according to the A0 map in section 6.2.1 and data analysis in section 5.3.3. LBW process planning is further decomposed into LBW process planning, skin fabrication process planning and stringer fabrication process planning, the inputs, outputs, controls and mechanics of each sub-action are identified and the description of each symbol is listed below in Figure 6-6.

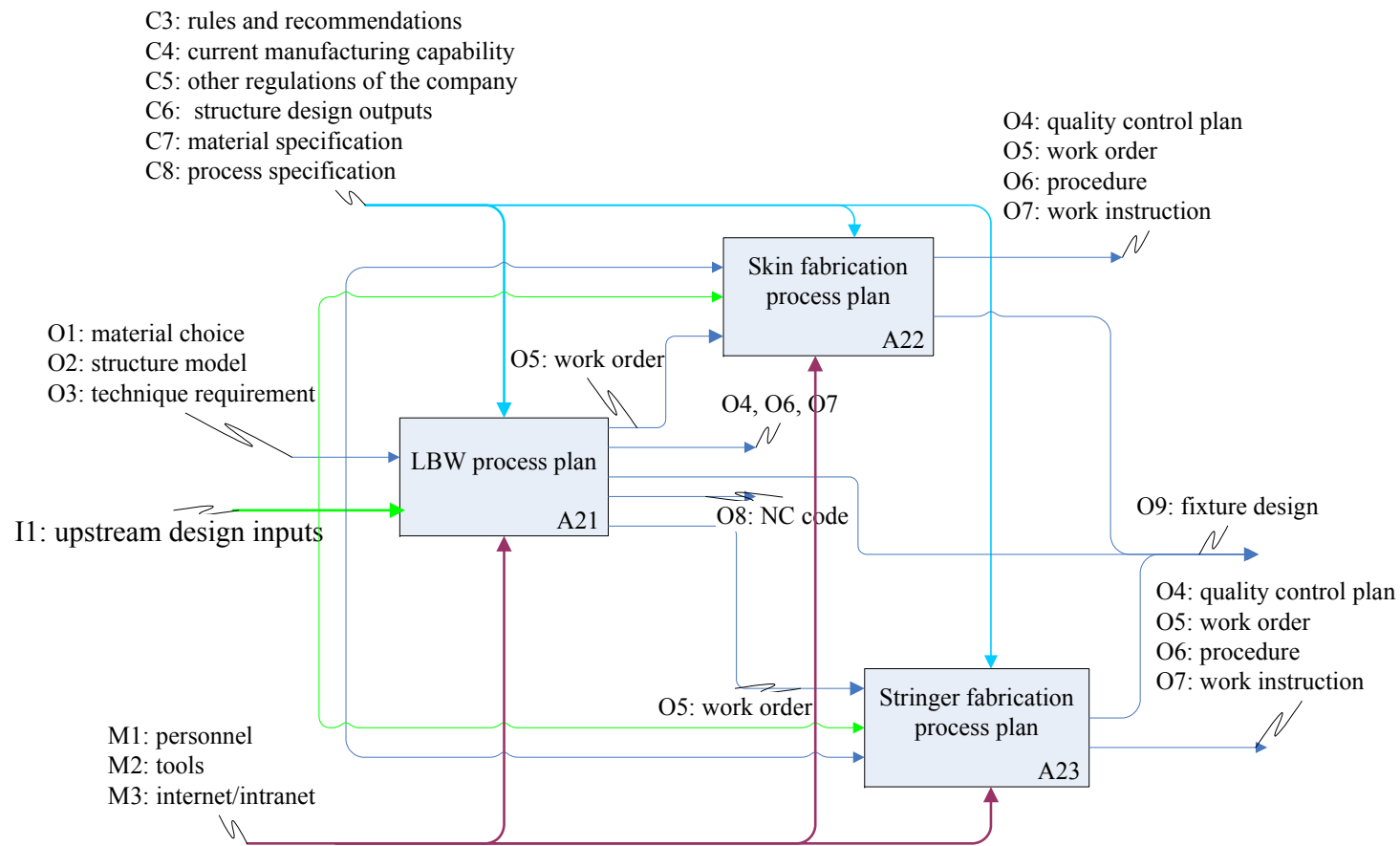


Figure 6-6 Decomposed IDEF0 map for A2: Laser Beam Welding process planning

After analyzing the inputs, outputs, controls and mechanics of the LBW process planning as well as the results from the data analysis, the main considerations are identified and classified into two aspects, namely process and resource as illustrated in Figure 6-7. All the considerations are implemented aiming to achieve the design requirement, including material and structure.

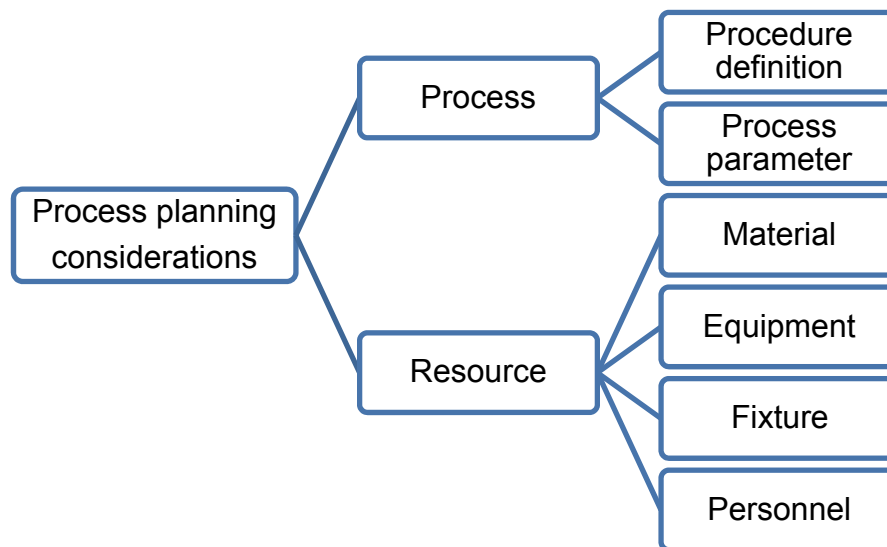


Figure 6-7 Categorization of process planning considerations

### 1) **Process:**

To develop and establish a reliable and validated procedure to make sure that the whole fabrication process is stable and under control is necessary, as it is a focus of airworthiness. The influence from each stage of the procedure should be considered in order to improve the results. Furthermore, the procedure should be validated within the industry environment as different conditions may influence the results. High quality laser welds are obtained only after optimization of key process parameters. So the process parameters should be optimized through performance testing (specimen, typical parts and analogue parts) and verification experiments, and the optimized parameters should be included in the Process Specifications so that they can be controlled.

## **2) Resource:**

Resource is always a strong support of process; no process can be completed successfully without resource. It can be categorized as material, equipment, fixture and personnel in the aircraft industry. What should be considered includes the quality of material, the accuracy and capability of the equipment, the efficiency of the fixture and the certification of operators. Taking fixture as an example, the workpiece should be located and clamped with a specific fixture to ensure good fit-up of parts, minimize gap and achieve the required laser beam/joint line alignment tolerances. When designing the fixture/tooling for LBW, the accessibility of the laser beam to the joint as well as the shielding gas used in the process should also be considered.

## **6.3 Knowledge Capture**

Based on the identified structure design and process planning considerations in section 6.2, knowledge about these considerations is captured in this chapter as Rules and Recommendations. The whole structure of the Rules and Recommendations Set (RRS) built in this thesis includes two aspects, Structure Design Rules and Recommendations (SDRR) and Process Planning Rules and Recommendations (PPRR) as shown in Figure 6-8. This is in line with the classification of considerations identified in section 6.2 in general, focusing on the product structure, procedure and parameters of the process and fixture.

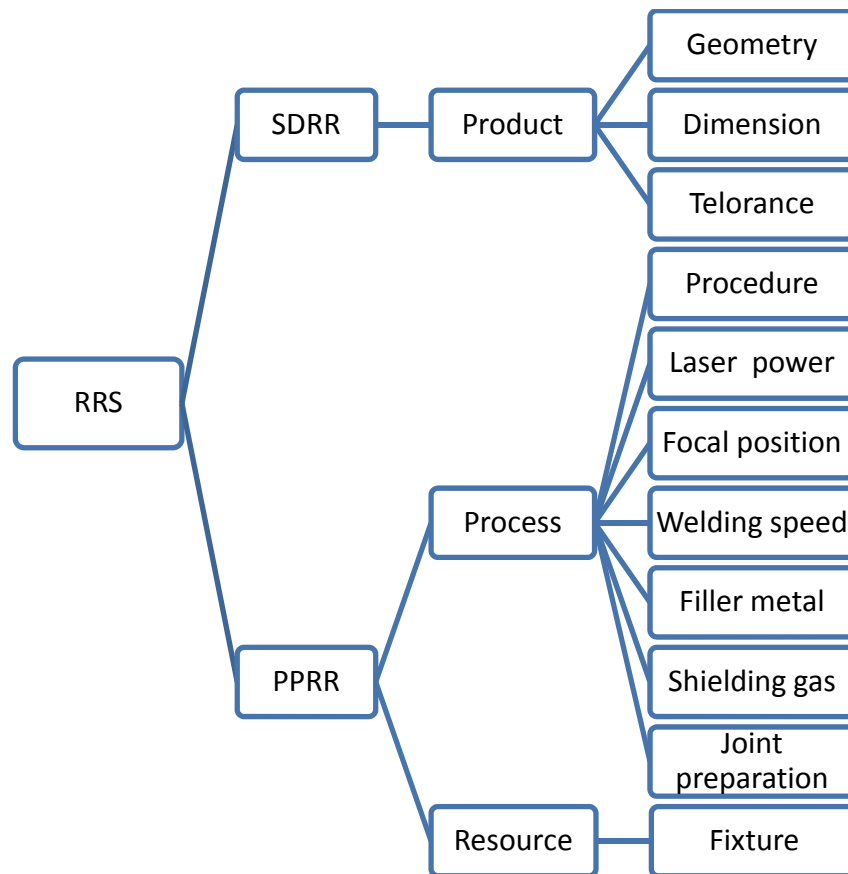


Figure 6-8 Categorization of captured knowledge about Laser Beam Welding

The following subsections will describe the methodology for knowledge capture and its outcomes in detail.

### 1) Rules and recommendations:

**Rules** check whether the structure designing and process planning are respecting the considerations. They are made up of a condition (“IF”) and an action or statement (“THEN”). The structure is illustrated in Figure 6-9.

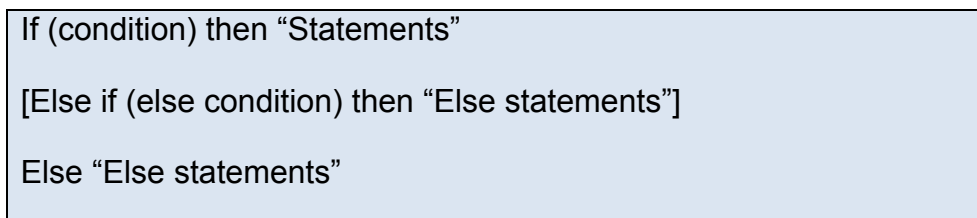


Figure 6-9 Structure of rules (Tamarit, 2010)

**Recommendations** suggest the suitable structure design and process planning solutions from experience, experiments and/or literature.

## 2) Examples of rules and recommendations:

Two examples of rules and recommendations are shown in Figures 6-10 and 6-11 regarding to structure design and process planning. The complete Rules and Recommendations Set (RRS) can be referred to in Appendix D.

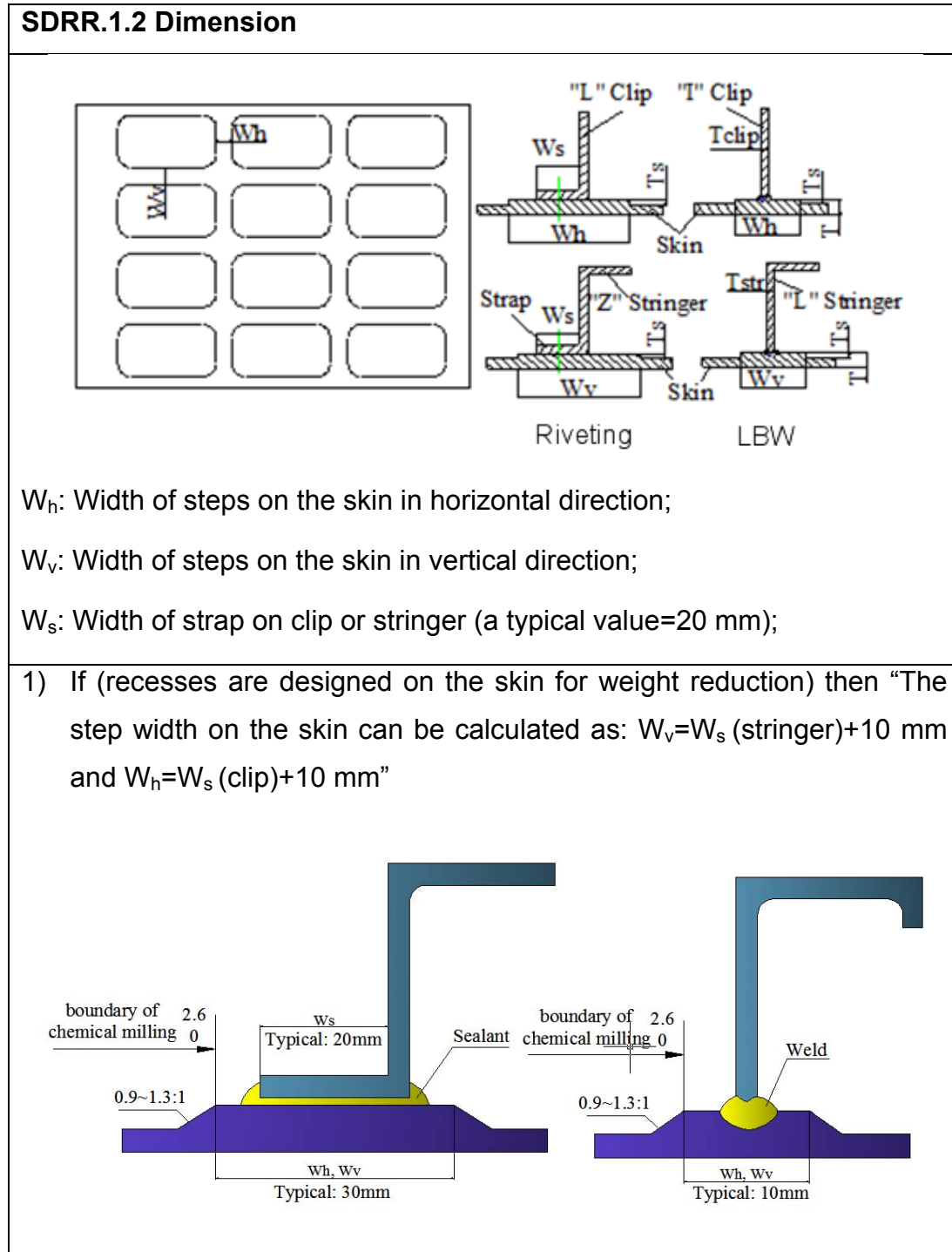


Figure 6-10 Example of rules and recommendations for product domain



### PPRR.1.2 Laser power

2) If ( $P \leq P_1$ ) then “the weld pools at two sides of the T butt joint separate, which results in low joint strength”

Else if ( $P_1 < P < P_2$  and  $P \uparrow$ ) then “weld width ( $W$ )  $\uparrow$ , weld depth ( $H$ )  $\uparrow$ , angle of weld profile ( $\gamma$ )  $\downarrow$ , angular distortion ( $\phi$ )  $\uparrow$ , deflection ( $\delta$ )  $\uparrow$ ”

Else if ( $P \geq P_2$ ) then “the skin is fully penetrated which induces the risk of sealing and dropout”

Where  $P_1$  is the critical power that makes the two weld pools of two sides of the T butt joint join together and  $P_2$  is the critical power that makes full penetration of the skin. These two critical powers are not constant in different conditions.

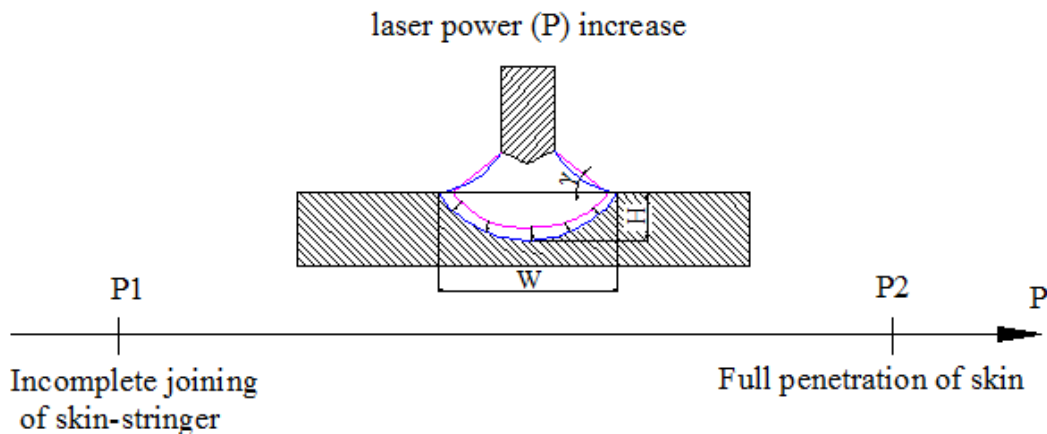


Figure 6-11 Example of rules and recommendations for process domain

## 6.4 Knowledge Representation

Based on the Product, Process and Resource (PPR) model introduced in section 5.3 and identified considerations in section 6.2, a further developed schematic diagram was built to represent the LBW process in the aircraft industry as shown in Figure 6-12. Before conducting LBW fabrication ③, component design for LBW ①, including joint type selection, skin and stringer structure design and weld definition and process planning ②, including LBW

process definition, the process parameter optimisation and resource preparation must be identified. All of these aspects can be guided by the developed rules and recommendations.

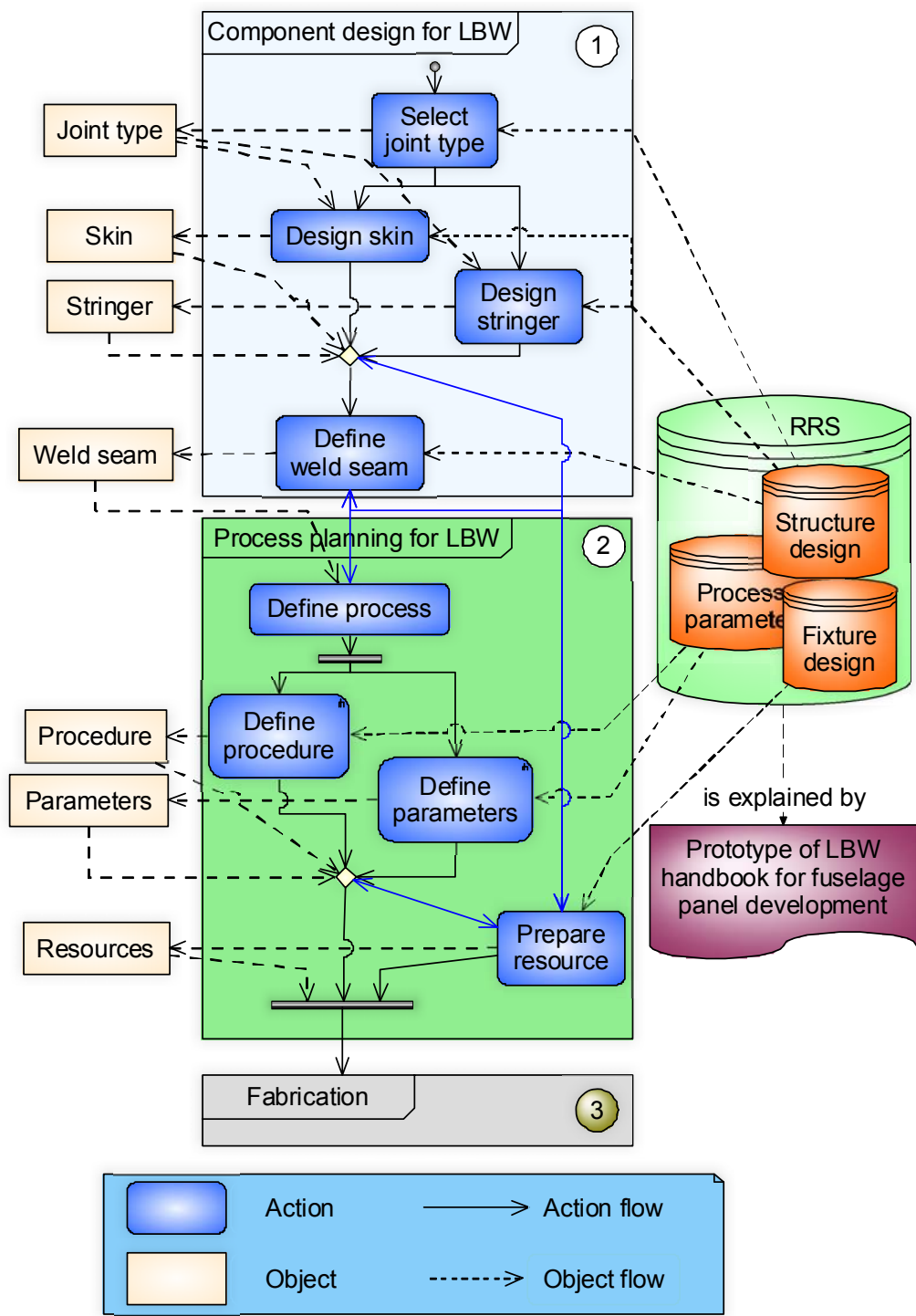


Figure 6-12 Schematic representation of Laser Beam Welding in the aircraft industry

A prototype of the LBW handbook for aircraft fuselage panel development was developed to illustrate the implementation of the knowledge, which can be referred to in Appendix E. Figure 6-13 presents the content of the handbook, including: an introduction of the principle, advantages and disadvantages of LBW as well as the application of LBW in the aircraft industry to develop the understanding of LBW process in the aircraft industry; structure design and process planning manual to guide designers and engineers on how to design a suitable structure for LBW to gain potential weight reduction; how to design a fixture for LBW to achieve accurate locating and clamping as well as good fit-up; and, how to optimise process parameters to gain sound as-welded geometry. Only six sample rules were contained in this prototype; however, each rule or recommendation is described and explained in detail, based on which, a complete understanding of the rule can be gained and the aim of sharing the knowledge can be achieved.

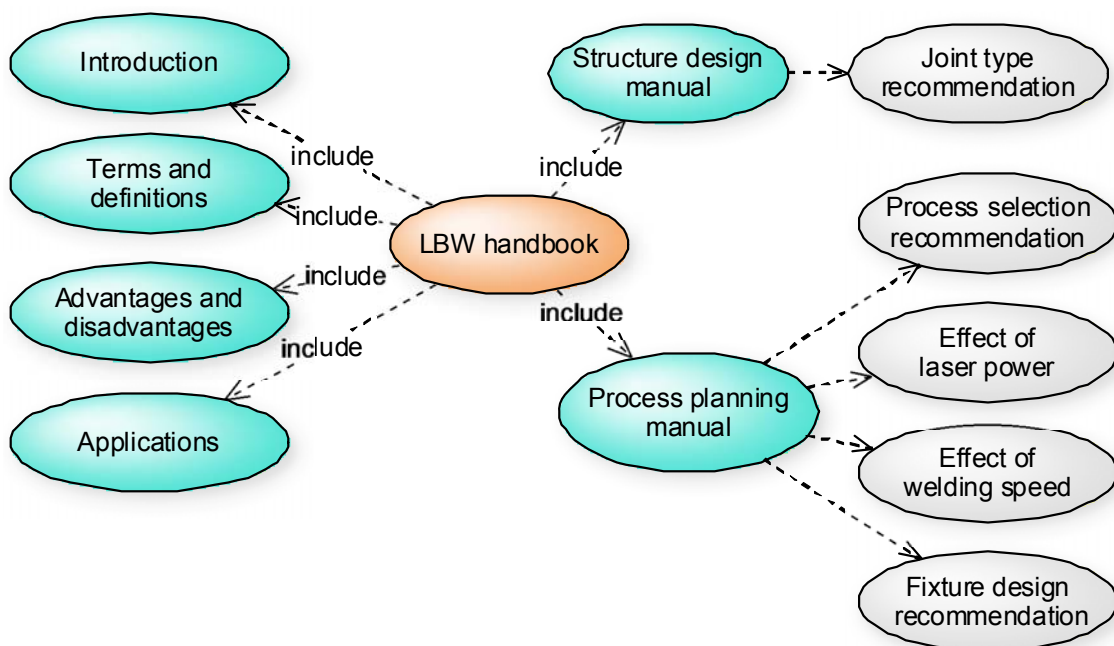


Figure 6-13 Content of prototype of LBW handbook for aircraft fuselage panel development

## **6.5 Summary**

First, the LBW component development procedure was analyzed in this chapter, based on which, the structure design and process planning considerations were identified through IDEF0 maps and classified with concept maps. Then, knowledge about these considerations was captured as rules and recommendations. Finally, a schematic diagram was built to represent LBW in the aircraft industry as well as the content of the prototype LBW handbook for aircraft fuselage panel development to illustrate the implementation of the captured knowledge.

## 7 Validation of key rules

### 7.1 Introduction

This chapter describes the systematic validation process. Five key rules were selected from the developed rules and recommendations and validated through a case study, literature and expert judgement. The strength, weakness and usefulness of the rules were evaluated by the experts and some improvements were adopted based on their comments and suggestions.

### 7.2 Validation Process

The validation process includes three steps as illustrated in Figure 7-1. Firstly, five key rules were selected from the developed Rules and Recommendations Set (RRS). Secondly, the selected key rules were demonstrated with a case study and the literature. Finally, they were validated by expert judgement. The expert judgement includes three stages, namely validation of sample rules for the initial categorization and representation style as well as for correctness, refining the key rules and further validation for weakness and usefulness of the key rules.



Figure 7-1 Schematic diagram of validation process

Two independent experts from COMAC and Cranfield were selected to take responsibility for validation, both of whom have rich experience of the LBW process. Table 7-1 presents a brief introduction of the experts. Because expert B is in China, it was not convenient to carry out a face-to-face interview for

validation. Thus, expert judgement by expert B was conducted through a questionnaire. A brief introduction to this project and the selected key rules were sent to the expert by email, as well as the questionnaire. The comments from expert B were collected by email. In contrast, judgement by the expert at Cranfield was conducted through a face-to-face interview. A presentation of this research as well as the developed rules and recommendations were conducted firstly for about fifteen minutes. The expert checked the key rules and discussed with the author for about one and a half hours. Comments were given to each of the selected key rules, which were also recorded in the questionnaire. The questions queried to the experts during the validation process are illustrated in Appendix F.

Table 7-1 Introduction of experts for validation

Expert	A (from Cranfield)	B (from COMAC)
<b>Position</b>	✓ Research fellow on LBW in the Welding Department	✓ Project team leader of Laser Beam Welded fuselage panel fabrication ✓ Associate Professor at Nanjing University of Aeronautics & Astronautics
<b>Experience</b>	✓ Over four years experience on LBW process	✓ Six years experience on LBW process ✓ Rich experience in the aircraft industry
<b>Validation method</b>	✓ Semi-structured interview	✓ Questionnaire

### 7.3 Selection of Key Rules

As the developed rules and recommendations are categorized as structure design and process planning, i.e. two main aspects, and product, process and resource, i.e. three domains, the selected key rules should cover all these domains. According to the different number of developed rules and recommendations in these three domains, five key rules were selected: one

from the product domain, three from the process domain and the last one from the resource domain as illustrated in Figure 7-2.

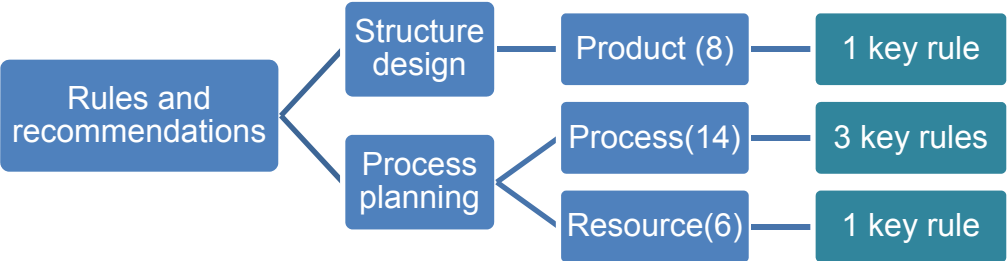


Figure 7-2 Distribution of key rules

For structure design, the rules and recommendations are about joint type selection, skin and stringer structure, including geometry, dimension and tolerance as well as material selection. As the selection of joint type is the first issue to be decided for structure design and is the source of potential weight reduction, it has been chosen as the key rule for structure design. Figure 7-3 illustrates all the related aspects about structure design for LBW which have been described in detail in the prototype of the handbook in Appendix E.

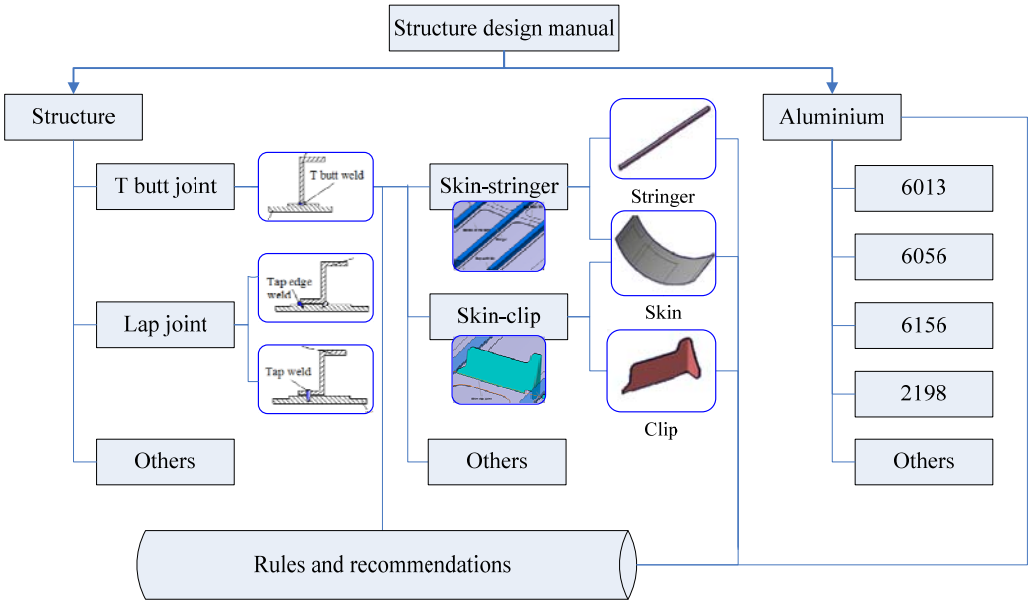


Figure 7-3 Structure of the structure design manual for Laser Beam Welding

The process planning is conducted based on the design inputs of structure and material. In this stage, the fabrication process must be defined, the process parameters should be optimized, and the fixture designed. One rule each for these three aspects was selected as key rules. As there are dozens of rules for process parameters, another key rule is selected from this aspect. Figure 7-4 illustrates the structure of process planning guidelines for LBW which also can be referred to from the handbook in Appendix E in greater detail.

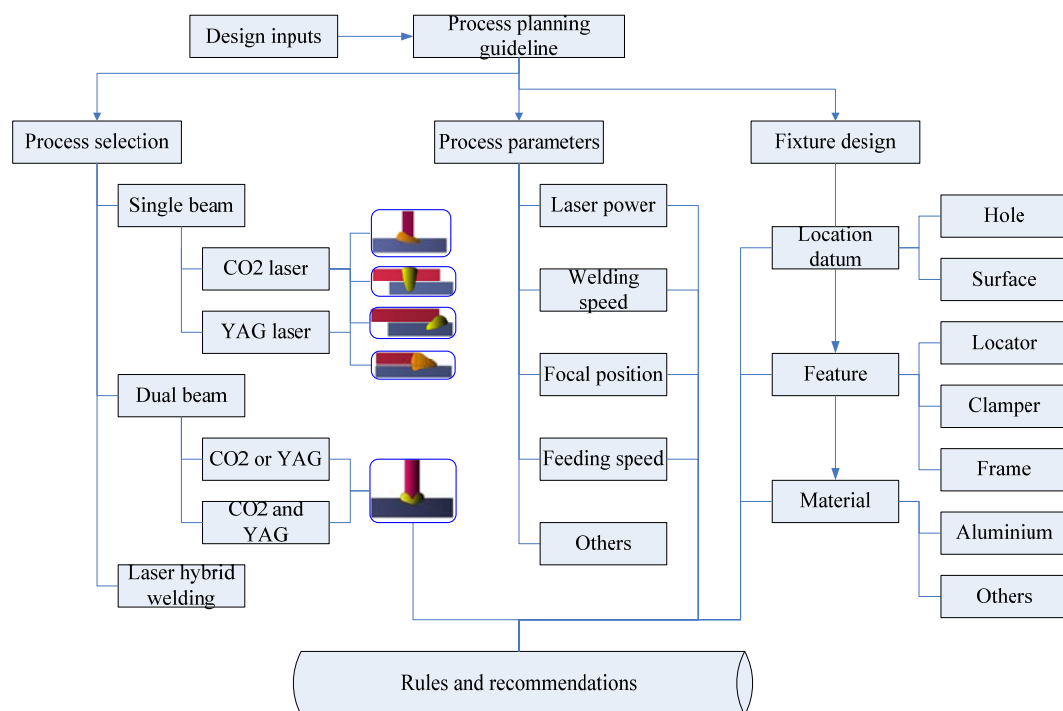


Figure 7-4 Structure of process planning guidelines for Laser Beam Welding

The selected key rules are listed as follows:

### 1) Skin-stringer joint type recommendation (Product)

“T butt joint is recommended for skin-stringer connection to achieve potential weight reduction”

### 2) Process selection recommendation (Process)

“Dual beam welding with two CO<sub>2</sub> lasers is recommended for skin-stringer T butt joint”



### 3) Effect of laser power on as-welded geometry (Process)

✚ If (laser power ( $P$ ) $\uparrow$ ) then “weld width ( $W$ ) $\uparrow$ , weld depth ( $H$ )  $\uparrow$ , weld angle ( $\gamma$ )  $\downarrow$ , angular distortion ( $\phi$ )  $\uparrow$ , deflection ( $\delta$ )  $\uparrow$ ”  
Else “ $W\downarrow$ ,  $H\downarrow$ ,  $\gamma\uparrow$ ,  $\phi\downarrow$ ,  $\delta\downarrow$ ”

### 4) Effect of welding speed on as-welded geometry (Process)

✚ If ( $V_w\uparrow$ ) then “weld width ( $W$ )  $\downarrow$ , weld depth ( $H$ )  $\downarrow$ , weld angle ( $\gamma$ )  $\uparrow$ , angular distortion ( $\phi$ )  $\downarrow$ , deflection ( $\delta$ )  $\downarrow$ ”  
Else “ $W\uparrow$ ,  $H\uparrow$ ,  $\gamma\downarrow$ ,  $\phi\uparrow$ ,  $\delta\uparrow$ ”

### 5) Stringer fixture design recommendation (Resource)

✚ “A stringer guiding system fixed to the working head is recommended to locate and clamp the stringer accurately as well as avoiding influence to the path of the laser beam”

## 7.4 Case Study

The selected five key rules were demonstrated in this section. The skin-stringer joint type recommendation was demonstrated with a case study; the process selection recommendation and stringer fixture design recommendation were demonstrated with literature; and, the effect of laser power and welding speed to as-welded geometry were demonstrated with experiment results from semi-structured interviews in COMAC.

### 7.4.1 Case Study: skin-stringer joint type recommendation

In order to demonstrate the potential weight reduction, a fuselage panel from a commercial aircraft was chosen for the case study as shown in Figure 7-5. The panel was originally designed for riveting with a “Z” type stringer and the dimension is 1731 mm x 2786 mm x 530 mm. The material for the skin is Al-Li alloy 2198 while the material for the stringer is Al-Li alloy 2099, both having good weldability. CATIA V5R18 is used for structure design and weight calculation. CATIA is the commonly used design software in the aircraft industry.

Following the rules and recommendations for structure design and only changing the stringer from “Z” type to “L” type as shown in Figure 7-5, the calculated weight reduction is 8.89%. This result corresponds with the data obtained from the literature, namely from 5% (Brenner et al., 2008) to 10% (Tempus, 2001) of weight reduction.

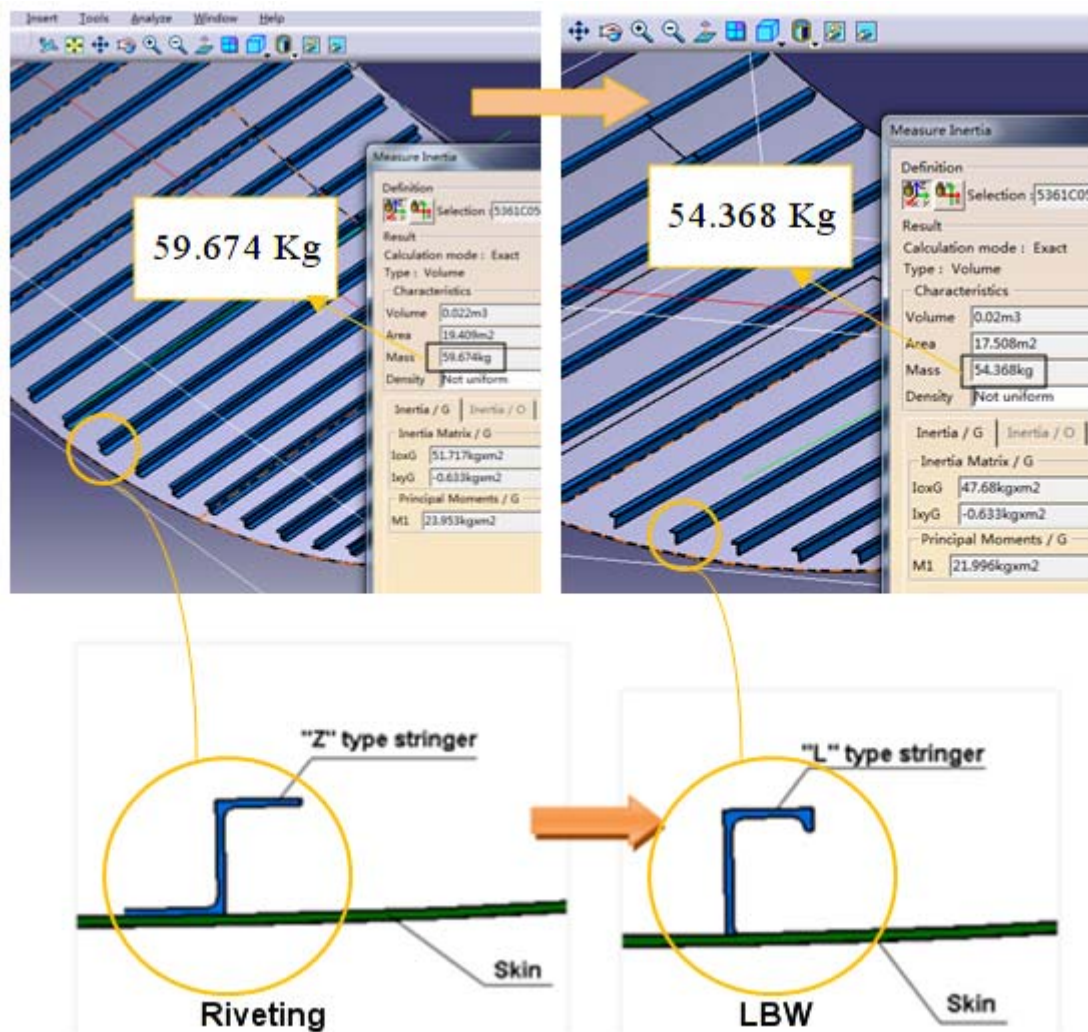


Figure 7-5 Potential weight reduction for Laser Beam Welding

#### 7.4.2 Process Selection Recommendation

The LBW process for stringer-skin T butt joints in Airbus was dual beam welding with two CO<sub>2</sub> Lasers of 3.5 kW beam power as illustrated in Figure 7-6 (Rendigs and Knowler, 2010; Kocak and Uz, 2009). The first low fuselage panel under this LBW process was proved in 2001 with required quality. Up to 2010, over

1200 panels have been produced and most of them are now in service. This fact taken from the literature is a strong demonstration of this recommendation. Actually, dual beam welding comes with less distortion than single beam welding for symmetric welding and better beam accessibility than Laser-X hybrid welding. CO<sub>2</sub> lasers are preferred because they are much cheaper than other types of lasers although their efficiency is low.

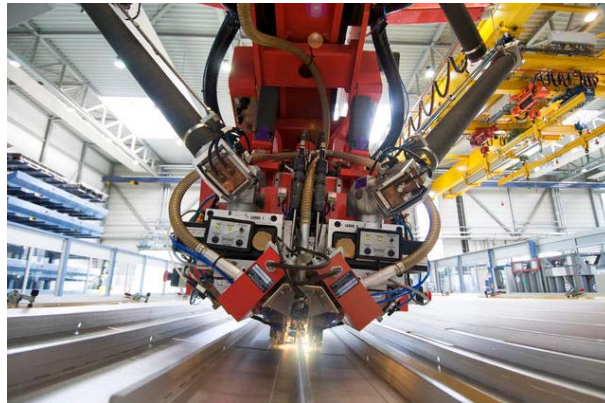


Figure 7-6 Dual beam welding of low fuselage panel with two CO<sub>2</sub> lasers  
(Source: Premium AEROTEC official website)

#### **7.4.3 Effect of laser power on as-welded geometry**

It is difficult to find detailed information from the literature to demonstrate this rule because of confidentiality issues. Thus, the information obtained from semi-structured interviews about experiments in COMAC was chosen for demonstration, which is illustrated in Figure 7-8 and 7-9.

The experiments carried out for testing the effect of  $P$  to  $H$ ,  $W$  and  $\gamma$  were on condition that  $V_w = 3.8 \text{ m/min}$  and  $V_f = 2.7 \text{ m/min}$  and the structure of these specimens is illustrated in Figure 7-7 with dimensions of  $200_{\text{mm}} \times 100_{\text{mm}}$ . The micrographs of weld geometry in different laser power are shown in Figure 7-8, which prove that the weld depth and width increase with the laser power. When the power is low, the welding mode is likely to be conduction welding and the weld pools at both sides of the T butt joint are separate. With the increase of laser power, the two pools become united and the weld angle decreases which results in a concave weld profile.

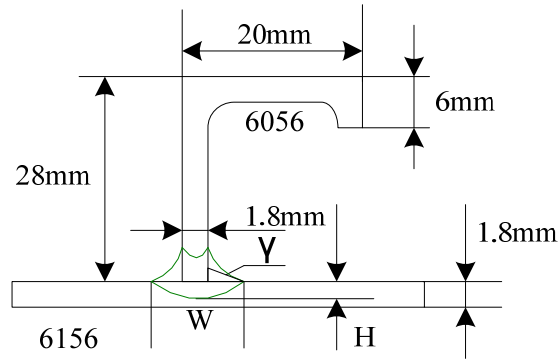


Figure 7-7 Schematic diagram of specimen structure (COMAC, 2011)

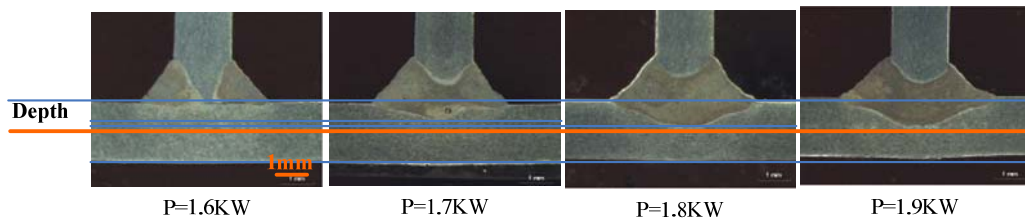


Figure 7-8 Effect of laser power to weld profile (COMAC, 2011)

The experiments carried out by COMAC for testing deflection were on condition that  $V_f = 2.7$  m/min and the dimension of specimens is 600 mm x 150 mm. The deflection includes deformation ( $\delta$ ) and angular distortion ( $\phi$ ). Figure 7-9 illustrates the effect of linear heat input ( $E'$ ) to deflection, which proves that both  $\delta$  and  $\phi$  increase with the  $E'$ . This is because the deflection is mainly caused by solidification shrinkage, which increases with the  $E'$  (Mandal, 2002). As  $E'$  increases with the  $P$  at the same time, thus, if  $P$  increases, the deformation increases.

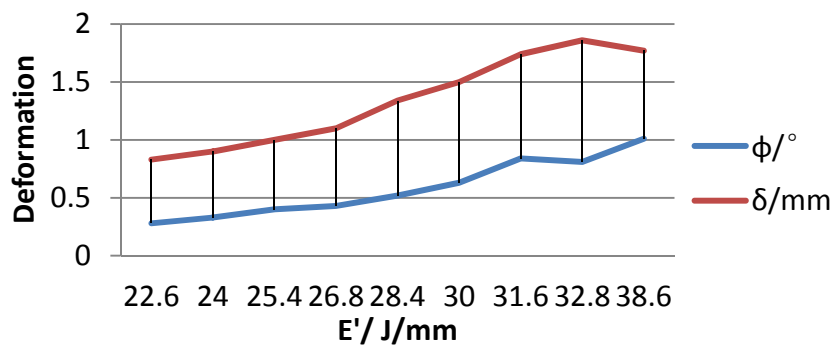


Figure 7-9 Effect of linear heat input to deformation (COMAC, 2011)

#### 7.4.4 Effect of welding speed on as-welded geometry

This rule is also demonstrated by the information obtained from semi-structured interviews about experiments in COMAC. The experiments carried out for testing the effect of  $V_w$  to  $H$ ,  $W$  and  $\gamma$  (refer to Figure 7-7) were on condition that  $P=1.8\text{KW}$  and  $V_f=2.7\text{ m/min}$  and the structure of specimens and dimensions was the same as the one introduced in section 7.4.3. Micrographs of weld geometry in four different  $V_w$  are shown in Figure 7-10, which prove that  $W$  increases while  $H$  decreases with  $V_w$ . In this case, when  $V_w$  is as low as 2.8 m/min, the skin is fully penetrated, which is not permitted. When  $V_w$  increases from 3.3 m/min to 3.8 m/min,  $\gamma$  increases. Li et al. (2011) also studied the influence of welding parameters on weld formation and microstructure of dual beam welded T butt joint of 6061 aluminium alloy, and they found that undercut is easily formed at relatively high or low  $V_w$ .

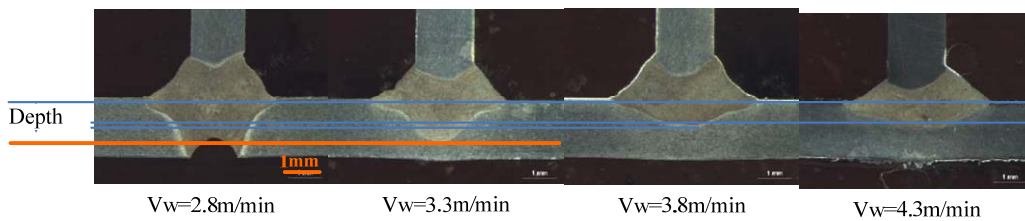


Figure 7-10 Influence of welding speed to weld depth (COMAC, 2011)

#### 7.4.5 Stringer fixture design recommendation

One demonstration of the stringer fixture is a stringer guiding system used in Airbus, which is illustrated in Figure 7-11. The left picture shows the welding head including the stringer guiding system, and the right one is a schematic diagram of the guiding system. This fixture is installed in the working head, so that there is no risk of interrupting the laser beam. Furthermore, as the rigidity of the working head is much higher than that of the stringer, it ensures the location of each part of the stringer during the welding procedure. This system has been applied to real production since 2001. Ten years' success in industry application has proved it to be a reliable solution for LBW of fuselage panels.

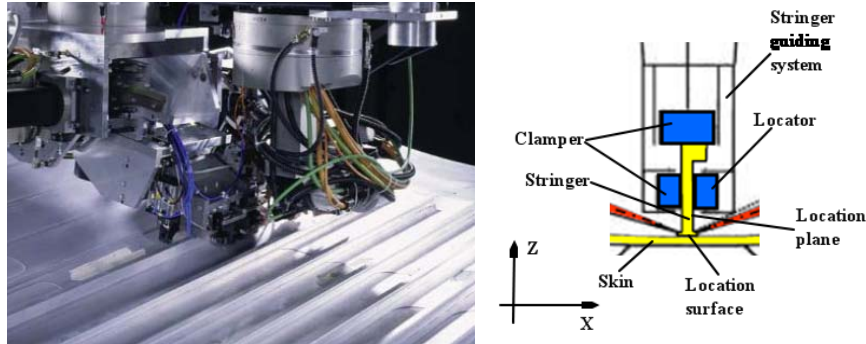


Figure 7-11 A typical stringer guiding system (Fraunhofer IWS, 2004; Rendigs and Knower, 2010)

## 7.5 Expert Judgement

### 7.5.1 Validation of Sample Rules

The samples validated by experts in COMAC and Cranfield are not completely identical because of the different expertise of the experts. “Skin-stringer joint type recommendation” and “Effect of laser power on as-welded geometry” were validated by the expert in COMAC while “Effect of laser power on as-welded geometry” and “Effect of welding speed on as-welded geometry” were validated by the expert in Cranfield, as illustrated in Table 7-2. A brief introduction to the research tasks and the developed rules and recommendations was presented to the experts at the beginning. Questions such as “What do you think about the categorization of rules and recommendations?” and “Is this rule easy to understand?” were queried, the questions for validation are recorded in Appendix F. This section will describe the comments for initial validation.

Table 7-2 Distribution of sample rules

Expert	Institute	Samples of key rules
<b>B</b>	COMAC	Skin-stringer joint type recommendation
		Effect of laser power on as-welded geometry
<b>A</b>	Cranfield	Effect of welding speed on as-welded geometry



The experts confirmed the categorization of rules and recommendations as they thought they were in line with the product development procedure as well as the potential users, namely structure designers and manufacturing engineers. However, they thought the conditions should be detailed for the rules, such as the specific material, equipment etc. and that it would be better to use diagrams to make the rules easy to understand. These comments were appreciated as they could contribute to the final representation of the rules. According to the former comment, a brief introduction to the conditions is added to the beginning of the rules and recommendations in Appendix D. In line with the latter comment, diagrams have been added to illustrate the rules wherever possible.

Expert B has validated the recommendation “T butt joint is recommended for skin-stringer connection to achieve potential weight reduction”, as he stated “It should be a basic understanding of the LBW process in the aircraft industry, and Airbus has given a powerful demonstration for this rule already.” He suggested the author should illustrate more possible joint types to support this rule more strongly, which has been taken into account and applied to this recommendation while also describing it in the handbook (see Appendix E).

For the rule “effect of laser power on as-welded geometry”, expert A indicated that the weld angle ( $\gamma$ ) in this research is confusing as its definition is different from the conventional one. Taking this into account, this angle is renamed as the angle of weld profile. Expert B agreed with this rule in general, but he thought “more process parameters, such as welding speed, incident angle, assembly gap and heat source clearance should be taken into account for the LBW process. All these parameters have a significant influence on as-welded geometry.” Therefore, most of the parameters he mentioned will be discussed in this thesis in other rules and recommendations.

For the rule “effect of welding speed on as-welded geometry”, expert A indicated that angle  $\gamma$  is likely to increase with the  $V_w$  as the heating and solidification time are both shortened and the flow rate of molten metal is accelerated. This effect should be much greater than the influence from the filler metal; however, this is different from the author’s opinion. As a result of expert

A's comment, the trend of  $\gamma$  was further studied and a much clearer understanding was developed and is reflected in the rules.

Through these approaches, the categorization, the representation style as well as the correctness of the sample rules were validated, based on which, possible refinements were applied to the five key rules and recommendations.

### 7.5.2 Refinement of Key Rules

The five key rules were refined based on the comments introduced in section 7.5.1. Two major refinements have been done to the rules, adding diagrams to these rules to make them easy to understand and detailing the conditions to make them clearer. Two examples of the refined key rules will be presented in this section and all the refined key rules can be referred to in Appendix D. According to these refined rules, a prototype of the handbook was also developed which is illustrated in Appendix E, aiming to guide structure design and process planning for aircraft fuselage panel development.

#### 1) Skin-stringer joint type recommendation after refining

✚ “T butt joint is recommended for skin-stringer connection to achieve potential weight reduction”

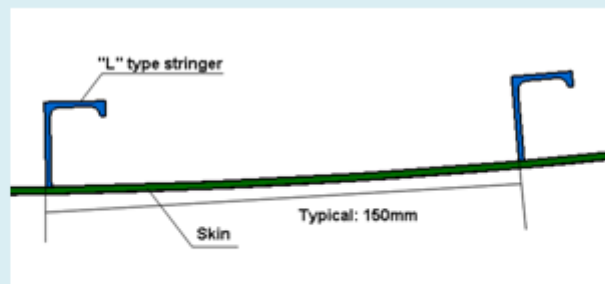


Figure E-5 A typical skin-stringer joint for Laser Beam Welding



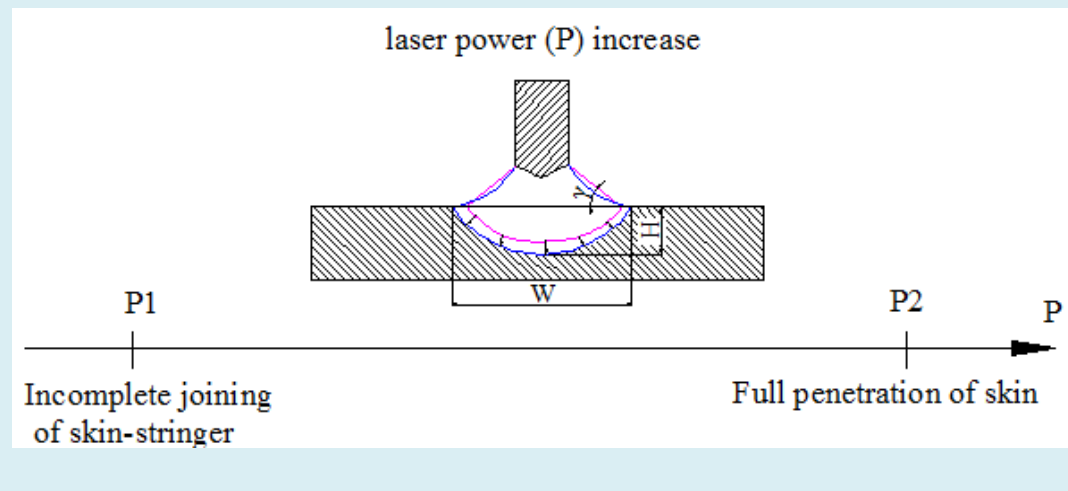
## 2) Effect of laser power on as-welded geometry after refining

✚ If ( $P \leq P_1$ ) then “the weld pools at two sides of the T butt joint separate, which result in low joint strength”

Else if ( $P_1 < P < P_2$  and  $P \uparrow$ ) then “weld width ( $W$ )  $\uparrow$ , weld depth ( $H$ )  $\uparrow$ , weld angle ( $\gamma$ )  $\downarrow$ , angular distortion ( $\phi$ )  $\uparrow$ , deflection ( $\delta$ )  $\uparrow$ ”

Else if ( $P \geq P_2$ ) then “the skin is full penetrated which induce risk of sealing and dropout”

Where  $P_1$  is the critical power that makes the weld pools from two sides of the T butt joint join together and  $P_2$  is the critical power that makes full penetration of skin. These two critical powers are always changing with the conditions.



### 7.5.3 Further Validation of Key Rules

All the five key rules were sent to the experts for further validation after being refined. Questions such as “What are the strengths and weaknesses of these rules and recommendations?” and “Do you think these rules can be applied to other industries?” were queried in the questionnaire. This section will present the comments for further validation.

The experts have confirmed that these rules and recommendations have given a basic guideline for the LBW process in the aircraft industry as they guide what structure to choose, how to design the fixture, and what will happen to the geometry if one parameter is changed. These aspects will contribute to the

structure design, fixture design and process parameter optimisation. Although this work only gives an estimate of the general trends resulting from a single parameter, it contributes to the foundation for further studies of many complicated phenomena and interactions and process parameters. This is where possible further research can be done.

The experts are optimistic about the application of rules and recommendations. They thought the rules about process planning could be applied to other industries, such as automotive and ship building, because the trends indicated by these rules would not be restricted by different material and structure. However, the rules and recommendations for structure design can only be applied to the aircraft industry as the structures for other industries are completely different. Expert B has also suggested that it is better to develop a quality assessment system or handbook for quality control of the LBW process, which can be another topic for further research.

Overall, the experts have confirmed the strengths and usefulness of these rules as well as indicating the weaknesses. As a result, the validation of key rules has been achieved.

## **7.6 Summary**

The validation process of the developed rules and recommendations has been presented in this chapter. Five key rules were first selected and demonstrated from the literature or case study. Semi-structured interviews and questionnaires were carried out with experts from COMAC and CU, respectively. Comments about the categorization, strengths, weaknesses and usefulness of the rules and recommendations were collected and analysed. Some valuable comments were adopted to improve all the developed rules and recommendations. Through all these approaches, the validation of these rules has been achieved.

## **8 Discussion and Conclusions**

### **8.1 Introduction**

After knowledge modelling, some rules and recommendations for structure design and process planning for LBW in the aircraft industry have been developed as well as a prototype handbook to illustrate the implementation of the knowledge. Five key rules have been selected and validated. The literature review, research methodology, planned aim and objectives as well as the contribution will be discussed in this chapter, after which the main conclusions will be given. Furthermore, the research limitations will also be discussed and further research will be suggested.

### **8.2 Discussion**

#### **8.2.1 Discussion of Literature Review**

Although there is little published literature about a knowledge model or rules and recommendations for LBW in the aircraft industry, which could be utilized directly in this research, a literature review was essential as the author had to build his own understanding of this research topic.

The literature review conducted in this research covers three domains: knowledge modelling, Laser Beam Welding and aircraft industry product development. From this approach, the author gained a fundamental knowledge about LBW including the principles, modes and methods, advantages, disadvantages, materials, structures, process parameters as well as existing applications of the LBW process in the aircraft industry. Based on this, a questionnaire was developed to collect information about the LBW process within the aircraft industry. A basic understanding of knowledge modelling was also achieved after this approach, including the knowledge life cycle, knowledge source and some common methods and tools for knowledge modelling, especially for process knowledge modelling. This contributed to the establishment of a research methodology for knowledge modelling. A review of

the aircraft industry product development procedures was also conducted so that the relationship with the aircraft industry product development procedure and the application of LBW was studied, which has influenced the LBW component development procedure. Furthermore, the research gaps discovered after the literature review have verified the research motivation and driven the author to focus on the establishment of rules and recommendations.

Because of the research scope, some important literature was not covered in this research. For example, knowledge-based engineering is not reviewed, which is essential for the implementation of knowledge after modelling. The applications of LBW in other industries, such as the automotive and ship building industries were not covered either. In fact, some of the knowledge captured from these industries about the LBW process can also be applied to the aircraft industry. This limitation of the literature review may have limited the captured knowledge.

### **8.2.2 Discussion of Research Methodology**

The four-stage qualitative research methodology adopted in this research, including understanding the context, data collection and analysis, knowledge model development and validation, proved successful in achieving all of the objectives of the project although some difficulties were encountered.

The literature review and unstructured interviews undertaken in the first phase succeeded in building a fundamental knowledge of this research topic and identifying the methods and tools for knowledge modelling. It also contributed to the design of questionnaire, which was utilized for data collection in the second phase.

Questionnaires, semi-structured interviews and a literature review together provided adequate data and information for knowledge modelling in general. However, the LBW process is a comparatively new technology for the investigated company. Most of the interviewees have only three to five years' working experience while some have five to ten years' experience. This

situation brings much difficulty to the data collection. The literature review played an important role in this phase. Much additional information was collected from this approach, although most of it was not detailed information about the LBW process in the aircraft industry.

The adopted methods and tools succeeded for knowledge modelling in the third phase. IDEF0 is proved to be an efficient tool for LBW structure development procedure modelling, based on which, the considerations of structure design and process planning were identified. The recommendations for structure design are capable of giving guidance to designers, so that they can make the design suitable for LBW at the beginning of the design stage. Based on the general trends of as-welded geometry to process parameters illustrated in the rules, the manufacturing engineers can know how to adjust the process parameters to achieve a sound as-welded geometry or quality. Thus, rules and recommendations are also efficient in this research. UML is used to build a systemic activity diagram of the LBW process in the aircraft industry to simplify the knowledge and make it suitable for sharing and training.

As there is little data for process parameter selection that can be collected from real production, some experiment results collected from semi-structured interviews in COMAC were relied on for the case study. However, the environment of experiments may be different from that of real production, which may induce risk to the optimised value of process parameters. Thus, only rules illustrating the general effect of process parameters to as-welded geometry were established and validated by the results of experiments.

### **8.2.3 Discussion of Achievement of Objectives**

This research aims to develop a knowledge model of the LBW process in the aircraft industry to improve structure design and process planning. This is accomplished through the achievement of five objectives, which are discussed in the following sub-sections.

**(i) Identify the methods and tools for knowledge modelling**

The identification of methods and tools for knowledge modelling were achieved through a literature review and unstructured interviews with experts and engineers in COMAC as introduced in chapter 4. A Knowledge Life Cycle (KLC) including knowledge identification, capturing and representation was identified firstly as it is in line with the development of Knowledge Management (KM) in the investigated company. The adopted methods and tools include IDEF0 and concept mapping for knowledge identification, rules and recommendations for knowledge capturing and UML for knowledge representation. All of these methods and tools are efficient and commonly used for knowledge modelling, which makes this approach general and possible to be applied to other process knowledge modelling.

**(ii) Identify the considerations for LBW structure design and process planning**

In order to identify the considerations for the LBW structure design and process planning, a questionnaire, semi-structured interviews and further literature review were conducted to collect data and information about the LBW process in the aircraft industry as presented in chapter 5. Over 20 interviewees were involved in the questionnaire and semi-structured interviews; however, most of them only have three to five years' experience of LBW, aircraft design, manufacturing or fixture design. This limited experience may bring a risk to the quality of collected information which has been discussed in section 5.3.1 in detail. Based on the collected information, an IDEF0 map was built to analyze the LBW structure development procedure. Through this analysis, the considerations of structure design and process planning were identified and categorized with a concept map as shown in section 6.2.

**(iii) Capture the knowledge about LBW structure design and process planning in the form of rules and recommendations, and represent them with UML**

Based on the categorization of considerations in section 6.2 and the collected information in chapter 5 as well as from the literature, some knowledge about joint type, stringer structure, the effects of process parameters on as-welded geometry and fixture design were captured as rules and recommendations, which are efficient forms of knowledge and commonly used in the aircraft industry as guidelines. Experts have confirmed that the rules can guide the structure design and fixture design efficiently so as to gain potential weight reduction. However, the rules for process parameter optimization only illustrate the effect of a single parameter generally, which will limit the contribution of these rules. UML is used to represent the knowledge schematically. However, only primary usage of UML was adopted in this research because it is only aimed at making the knowledge easy to understand and suitable for sharing or training. A prototype handbook was developed to illustrate the implementation of the knowledge. When aiming to implement these rules and recommendations into software, the representation can be further implemented.

**(iv) Apply the captured knowledge to a fuselage panel of a commercial aircraft**

A case study of structure design rules and recommendations was conducted to validate the potential weight reduction. It was carried out by changing the “Z” type stringer to an “L” type to make the structure suitable for LBW. The selected object was a low fuselage panel from a commercial aircraft and the design environment was CATIA V5R18, which is commonly used for structure design in the aircraft industry. The resulting weight reduction was compared to the data obtained from literature, which are about the application of the LBW process for low fuselage panels in Airbus. It was found that the two are compatible. This case study is also limited as it has not covered the rules for process parameter selection and fixture design.

**(v) Validate the developed model through case study and expert opinion**

After all of the previous objectives have been achieved, the knowledge modelling procedure has also been achieved. Next, a validation approach was conducted. Five key rules were selected and validated using the literature or case study as well as expert judgement. Based on the valuable comments from experts, some improvements were applied to the developed rules. The experts have confirmed the rationality, strength, weakness and usefulness of these rules, which means the validation is achieved.

### **8.3 Contribution to Knowledge**

The main contributions of this research include the captured knowledge about structure design and process planning for LBW in the aircraft industry in the form of rules and recommendations, the developed LBW handbook for aircraft fuselage panel development and the knowledge modelling procedure.

The rules and recommendations have developed the understanding of the LBW process in the aircraft industry and benefit the LBW structure development, including structure design, process parameter optimization and fixture design. The developed handbook based on the skin-stringer connection guides designers and engineers directly when developing a Laser Beam Welded fuselage panel, which is an implementation of the rules and recommendations. Furthermore, the knowledge modelling procedure including identification, capturing and representation of the knowledge as well as the methods and tools adopted can be applied to other process knowledge modelling as all the adopted methods and tools are commonly used for knowledge modelling.

### **8.4 Conclusions**

This thesis has described the knowledge modelling approaches for the LBW process in the aircraft industry, which is a necessity for expanding its application. Questionnaires, semi-structured interviews and a literature review were



conducted for data collection, whilst IDEF0, concept map, rules and recommendations and UML were utilized for knowledge identification, capture and representation. A set of rules and recommendations as well as a prototype handbook was developed to guide the designers and engineers for structure design, process parameter optimization and fixture design. Some key rules were selected and demonstrated from the literature or case study and validated by expert opinion. The results of this research can be summarised as follows:

- 1) Structure design rules and recommendations guide structure designers to design suitable structure for LBW to maximize its advantages
- 2) Process planning rules and recommendations guide manufacturing engineers to optimize process parameters to achieve the required as-welded geometry as well as giving some basic guidelines to the fixture designers to make their design suitable for LBW.
- 3) The prototype handbook has developed the understanding of the LBW process in the aircraft industry and detailed the application of rules and recommendations.

## **8.5 Research Limitations**

This research focused on LBW of skin-stringer connections on a fuselage panel, because it is the major source of weight reduction and is a simple repeating and time-consuming job which is extremely suited to LBW. The rules and recommendations for skin and stringer structure design cannot be applied to other industries, which is the limitation of these rules. Furthermore, only the effect of process parameters on as-welded geometry was studied for process planning, the effects of these parameters to defects as well as the interactions of these parameters were not covered in this research, which also limits the contribution of these rules and recommendations.

## **8.6 Further Research**

According to comments from experts and the discussion about research limitations, there are some areas that have not been covered in this research and further research could be performed to enhance the set of rules and

recommendations. These possible researches areas include but are not limited to:

- ✓ Studying the effect of process parameters on defects, such as pores and hot cracking.
- ✓ Studying the interactions of process parameters to find an optimized set of process parameters.
- ✓ Developing a quality control system or handbook with assessment standards of LBW process in the aircraft industry.

Considering the KLC of the developed rules and recommendations, there is also further work that could be done in the future:

- ✓ Developing an advisor system which is compatible with the structure design and fixture design software in order to implement these rules and recommendations.

## **8.7 Summary**

The literature review, research methodology, achievement of objectives and contributions to knowledge of this research have been discussed in this chapter, based upon which, conclusions have been given. According to the comments during the validation in chapter 7, and discussion in sections 8.2 and 8.3, some research limitations and possible areas for further research were also discussed.

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## APPENDICES

### Appendix A Questionnaire——Capturing the Laser Beam Welding process capabilities in the aircraft industry

This questionnaire is part of MSc research project entitled “Knowledge modelling for LBW process in the aircraft industry” aiming to collect information about LBW process in the aircraft industry. With the collected information, a knowledge model about the LBW process would be built aiming to guide engineers for designing welding structure and making welding strategy.

Thanks for participating this research. The analysis results can be sent to you if required. And the gathered data will be processed under the confidential protection. The original records will be destroyed when the thesis is completed and not be spread to any other organization or person.

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**Note:** Please write the letter of your choice(s) (e.g. A, B, or C ...) in the box or write your answer on the line below the question. If other, please list it out.

Name(optioned):

Company/Institute (optioned):

---

---

#### A.1 General Information

G1. Please choose the type of your company/Institute? (Please choose the most suitable option)

- |                                   |                  |
|-----------------------------------|------------------|
| A. Aircraft manufacturing company | B. R&D Institute |
| C. University                     | D. Other         |

**Other:**

---

G2. What is your job? (Please choose the most suitable option.)

- A. Design engineer                      B. Manufacturing engineer  
C. Researcher                          D. Student  
E. Other

**Other:**

---

G3. How long have you worked at this job?

- A. Ten years or more                      B. Five to ten years  
C. Three to five years                      D. One to three years  
E. Less than one year

G4. Which of the following domains have you ever known about, or have experience on?

- A. Laser Beam Welding (LBW)  
B. Aircraft structure design  
C. Manufacturing process planning in aircraft industry

## **A.2 Laser Beam Welding process capabilities**

L1. From your experience, what are the greatest advantages of LBW process within aircraft industry, comparing with traditional joining processes? (You can choose four options at most)

- A. Weight saving                      B. Structure complexity                      C. Material consumption



- |   |                            |
|---|----------------------------|
| E. Protection gas                         | F. Surface preparation     |
| G. Gap between components<br>being welded | H. Initial residual stress |
| I. Welding nozzle geometry                | J. Other                   |
| K. Not sure                               |                            |

**Other:**

**Reason:**

L4. From your experience, what are the vehicles of LBW process capabilities (methods and tools to ensure LBW process capabilities) within aircraft industry? (You can choose as many options as you wish).

- |                            |                        |
|----------------------------|------------------------|
| A. Laser welding equipment | B. Fixture/Tool        |
| C. Technique requirement   | D. Work instruction    |
| E. Quality control         | F. Surface preparation |
| G. Process specification   | H. Material control    |
| I. Personnel               | J. Process simulation  |
| K. Other                   | L. Not sure            |

**Other:**

L5. From your experience, what type of Aluminium is already used in LBW process within aircraft industry and what is the potential one would be used in the nearly future? Please choose the series and identify the unique type.

Example of answer:

C	6056
---	------

Aluminium already been used:


Aluminium potential to be used:


- A. 2xxx Series: such as 2024, 2027, 2050, 2524
- B. 5xxx Series: such as 5083, 5059
- C. 6xxx Series: such as 6013, 6056, 6156
- D. 7xxx Series: such as 7040, 7050, 7075, 7085, 7349, 7449
- E. Al-Li alloy: such as 1420, 2090, 2098, 5A90
- F. Other
- G. Not sure

**Other:**

---

L6. Which are essential stages for LBW process? Can you give an idea procedure for LBW process? (You can choose as many options as you wish).

--

- A. Workpiece preparation
- B. Pre-welding treatment
- C. Locate the workpiece
- D. Clamping the workpiece with fixture
- E. Adjust process parameter
- F. Conduct welding
- G. Release the fixture
- H. Post-welding treatment
- I. Inspection
- J. Process simulation
- K. Other
- L. Not sure

**Other:**

---



**Ideal procedure of LBW process:**

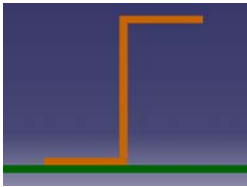
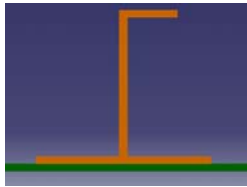
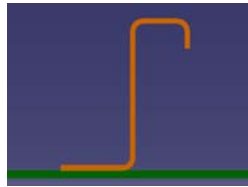
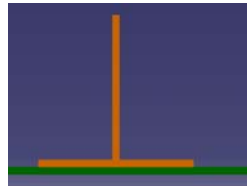

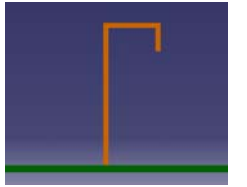
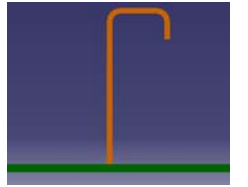
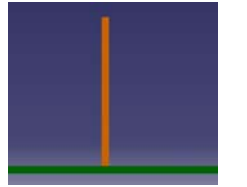
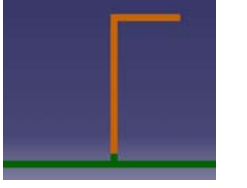



L7. What should be taken into account when designing the LBW joints (skin-stringer)? (You can choose as many options as you wish)

- |                            |                                    |
|----------------------------|------------------------------------|
| A. Weldability of material | B. Capability of welding equipment |
| C. Skin geometry           | D. Skin manufacturing method       |
| E. Stringer geometry       | F. Stringer manufacturing method   |
| G. Tolerance               | H. Dimension                       |
| I. Other                   | J. Not sure                        |

**Other:**

---

L8. Which of the following joint type will you choose for LBW in aircraft industry? ( you can choose four options at most)

A. 	B. 	C. 	D. 
E. 	F. 	G. 	H. 
I. 	J. 	K. 	L. 
M. Other	N. Not sure		

**Other:**

L9. What should be taken into account when planning LBW process? (You can choose as many options as you wish)

- |                       |                      |
|-----------------------|----------------------|
| A. Design requirement | B. Welding equipment |
| C. Fixture            | D. Laser power       |
| E. Welding speed      | F. Focal position    |
| G. Shielding gas      | H. Filler metal      |
| I. Other              | J. Not sure          |

**Other:**

---

L10. LBW process has already been applied to the manufacturing of fuselage panel of Airbus A318, A340 and A380, do you know about it? ('Yes' or 'No') If 'Yes', Where do you know about it?

Source : \_\_\_\_\_

L11. What do you think about the application of LBW process in Airbus? Give a reason for your choice, if possible. (choose the most suitable option)

- |   |   |
|---|---|
| A. A very good practise and can be identified as external benchmark | B. A good practise and can be identified as internal benchmark                    |
| C. A practise proving the applicability of LBW process              | D. A practise not successful enough to promote the spreading in aircraft industry |
| E. Other  | F. Not sure   |

**Other:** \_\_\_\_\_

**Reason:** \_\_\_\_\_

L12. What is your attitude about developing LBW process capabilities and applying LBW process in aircraft industry? Give reason for your choice, if possible.

- |                    |                |
|--------------------|----------------|
| A. Very support    | B. Support     |
| C. Partial support | D. Non-support |
| E. Reject          | F. Other       |

**Other:** \_\_\_\_\_

**Reason:** \_\_\_\_\_

### A.3 Capturing the Laser Beam Welding process capabilities

K1. From your experience, what are the most important benefits of capturing the LBW process capabilities in aircraft industry? (You can choose four options at most) If you choose 'Other', please type it out and give your reason, if possible.

- A. Promote knowledge management of LBW process
- B. Ensure and promote the LBW process capabilities
- C. Contribute to welding structure design
- D. Facilitate continual improvement of LBW process capabilities
- E. Accelerate and spread the application of LBW process
- F. Benefit making welding strategy
- G. Reduce the manufacturing cost of a certain component
- H. Other
- I. Not sure

**Other:**

---

**Reason:**

---

K2. Which do you think are the difficulties of capturing the LBW process capabilities? (You can choose four options at most)

- |                           |  |
|---------------------------|--|
| A. No definite definition | B. No existing method or procedure                                   |
| C. Too many factors       | D. Less industry application, not enough statistics from application |
| E. No systemic research   | F. Difficult to grasp comprehensive data as secrecy reason           |

G. Other

H. Not sure

**Other:**

---

K3. Do you think it is necessary to capture the LBW process capabilities?  
(‘Yes’ or ‘No’) Please give your reasons from your experience, if possible.

**Reason :**

---

K4. Please write down any words you would like to give this project.  
(suggestion or comment)

**Suggestion :**

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*End of questionnaire.*

*Thanks for your time.*

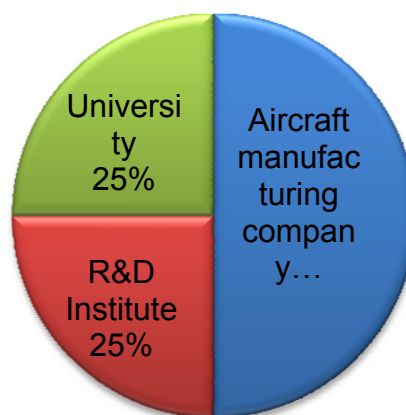
*E-mail: [x.sun@cranfield.ac.uk](mailto:x.sun@cranfield.ac.uk)*

## Appendix B Results of questionnaire

### B.1 General Information

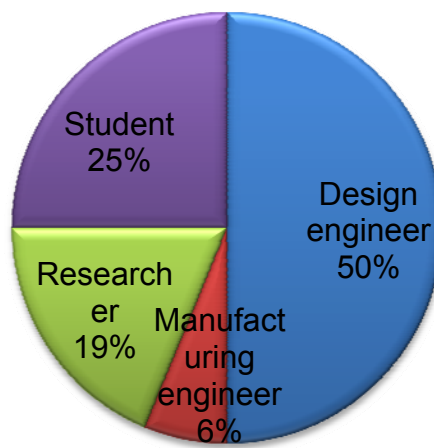
**G1. Please choose the type of your company/Institute? (Please choose the most suitable option)**

There are 16 interviewees who answered this questionnaire in all, 8 from an aircraft manufacturing company in China, 4 from an R&D institute (aircraft design) and others from a university in China too. The distribution is illustrated in the following pie chart.



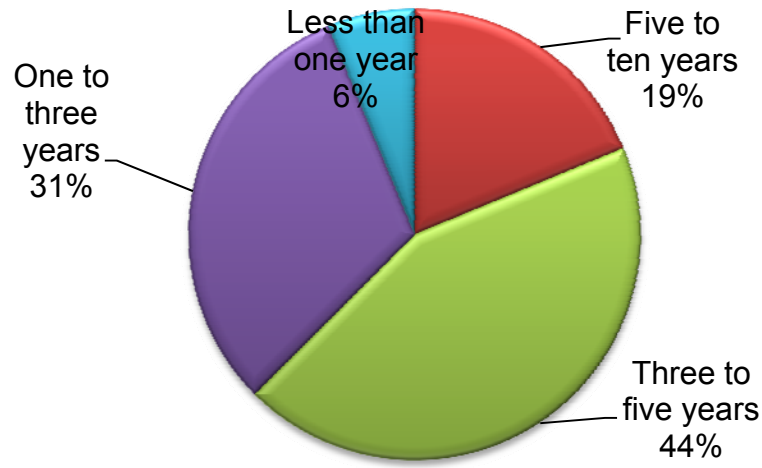
**G2. What is your job? (Please choose the most suitable option)**

Among the interviewees, 8 (50%) are design engineers (4 for aircraft structure design and the others for tooling/fixture design) and 3 (19%) are researchers with LBW process in COMAC. The others include one manufacturing engineer and 4 (25%) university students (2 Masters & 2 Doctorates) who are also in the LBW process research project in COMAC.



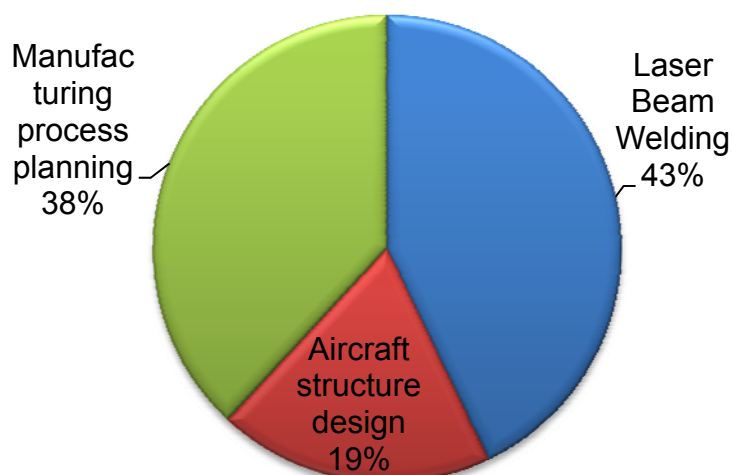
### G3. How long have you worked at this job?

As illustrated in the bar chart, 7 (44%) interviewees have three to five years' experience in their current position whilst another 5 (31%) interviewees have one to three years' experience. Only 3 (19%) has five to ten years experience but no one has over ten years experience.



### G4. Which of the following domains have you ever known about, or have experience of?

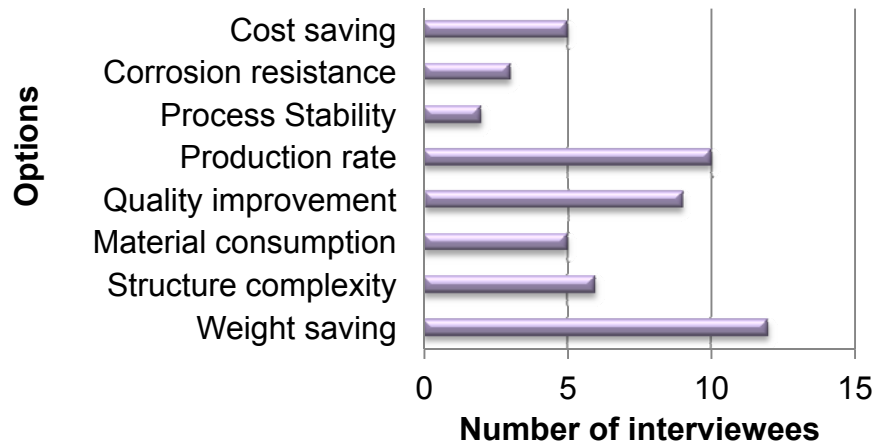
As presented in the following bar chart, 43% of the interviewees have ever known about or have experience on LBW and 38% of the interviewees have experience on manufacturing process planning. Only 19% of them have experience on aircraft structure design.



## B.2 Laser Beam Welding process capabilities

**L1. From your experience, what are the greatest advantages of the LBW process within the aircraft industry, compared with traditional riveting processes? (You can choose four options at most)**

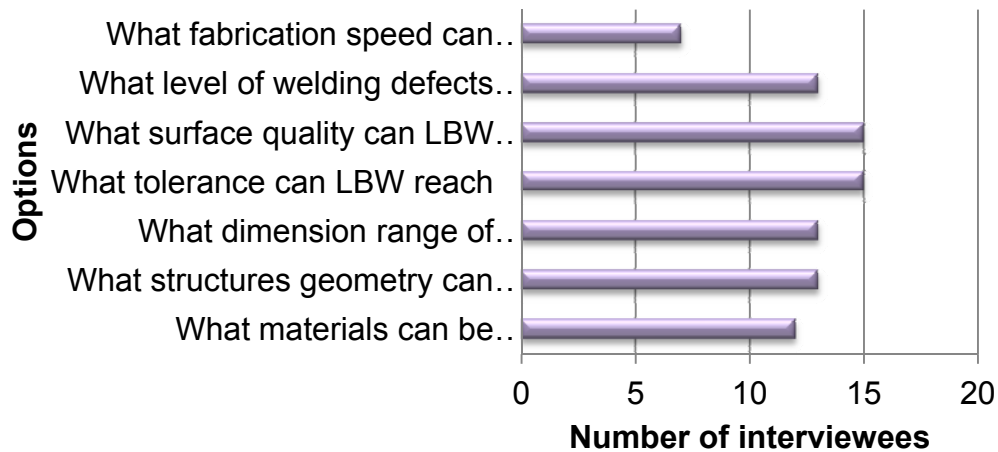
The first choice for question L1 is “weight saving”, which has been chosen by 12(75%) interviewees. This result is in line with the information obtained from literature. The options taking the second and third place are “production rate” and “quality improvement”, which have been chosen by 10 (63%) and 9 (56%) interviewees respectively. Only 2-3 (13%-19%) interviewees chose “process stability” and “corrosion resistance”. The complete answers are illustrated in the follow bar chart.



**L2. From your experience, which options can express the LBW process capabilities within the aircraft industry to a certain extent? (You can choose as many options as you wish)**

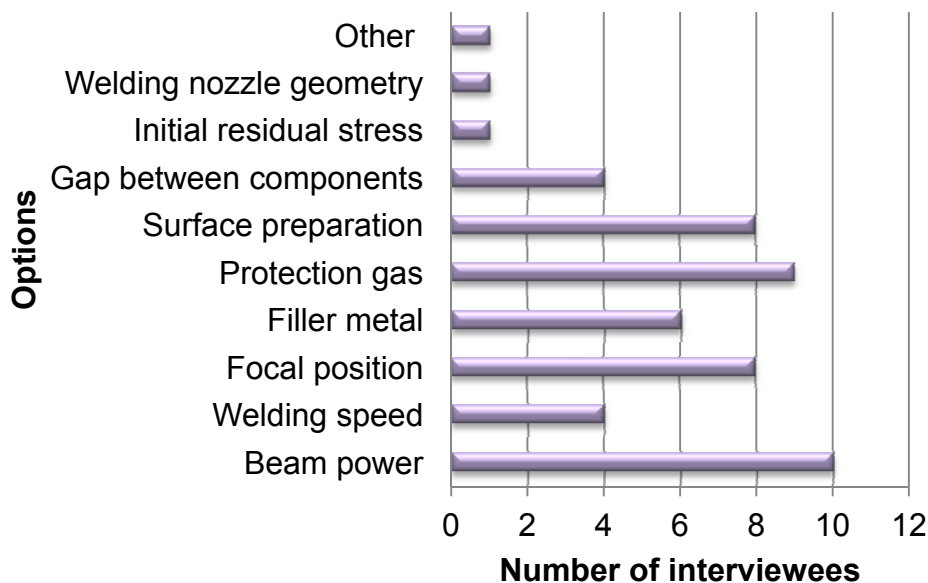
12-15(75%-94%) interviewees thought material, geometry, dimension range, tolerance, surface quality and welding defects level can express the LBW process capabilities within the aircraft industry to a certain extent, while 7 (44%) considered fabrication speed to be another aspect of LBW process capabilities.





**L3. From your experience, what are the most important factors of LBW process capabilities within the aircraft industry? (You can choose five options at most)**

8-12 (50%-63%) interviewees chose “beam power”, “protection gas”, “focal position” and “surface preparation” as the most important factors of LBW process capabilities within the aircraft industry while 4-6 (25%-38%) interviewees have chosen “filler metal”, “welding speed” and “gap between components”. Only one interviewee has chosen “initial residual stress” and “welding nozzle geometry”. Position of filler metal is also pointed out as it would influence the welding stability.



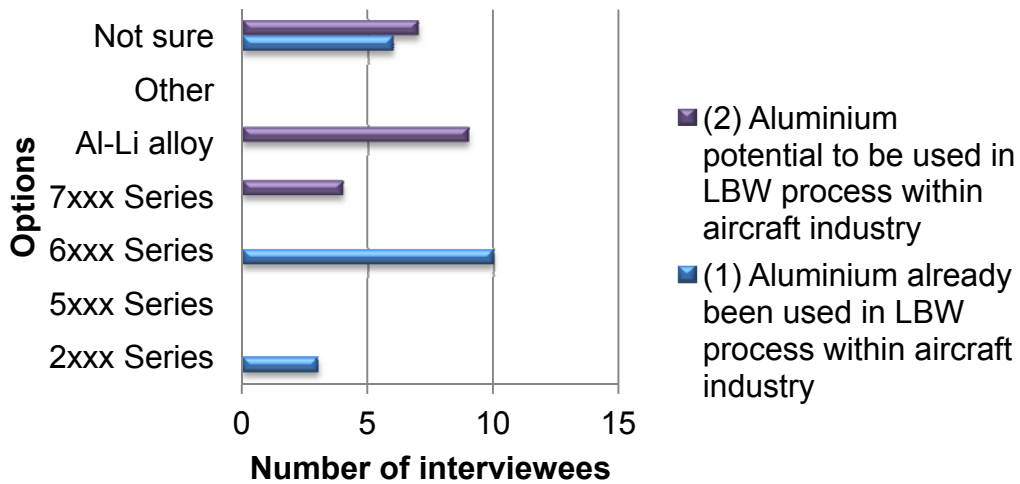
**L4. From your experience, what are the vehicles of LBW process capabilities within the aircraft industry? (You can choose as many options as you wish)**

8-13(50%-81%) interviewees chose “laser welding equipment”, “quality control”, “process specification”, “fixture/tooling”, “surface preparation”, “technique requirement” and “material control” as efficient methods to ensure the LBW process capabilities within the aircraft industry, while 4-6 (25%-38%) chose “work instruction”, “personnel” and “process simulation”.



**L5. From your experience, what type of Aluminium is already used in the aircraft industry and what is the potential one? Please choose the series and identify the unique type.**

10 (63%) interviewees identified that “6xxx series” aluminium alloys have been used in the aircraft industry for the LBW process, such as 6013, 6056 and 6061, while 3 of them also chose “2xxx series”. For the aluminium potential to be used, 9 (56%) interviewees chose “Al-Li alloys”, examples are 2198, 2196, 2099, 2090 and Al-Li-S-4, while 4 (25%) interviewees identified the “7xxx series”, examples are 7075 and 7050.



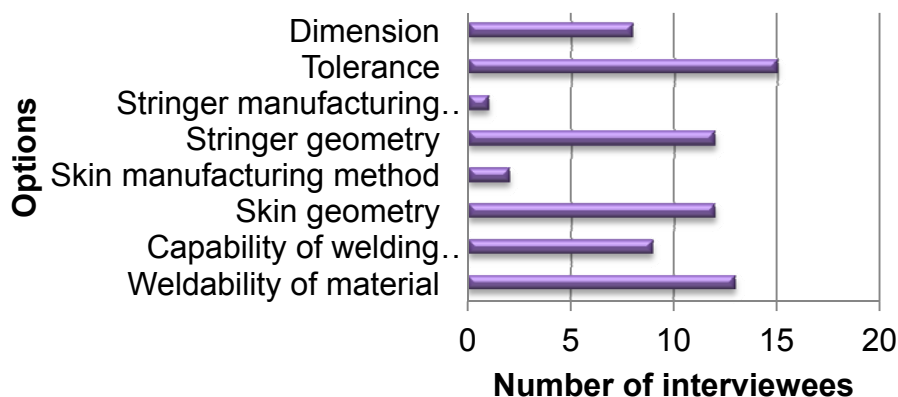
**L6. Which are essential stages for LBW process? (You can choose as many options as you wish)**

10-13 (63%-81%) interviewees chose “workpiece preparation”, “pre-welding treatment”, “workpiece location” and “clamping”, “process parameter adjustment”, “welding”, “release the fixture”, “post-welding treatment” and “inspection” as essential stages of the LBW process. Only 2 have chosen process simulation and 1 was not sure. From this question, the process structure can be basically identified as most interviewees have similar opinions.




**L7. What should be taken into account when designing the LBW joints (skin-stringer)? (You can choose as many options as you wish)**

The first issue to be considered in structure design is “tolerance” according to the questionnaire, as 15 (94%) interviewees have chosen this option. In fact, tolerance is always a key consideration in the aircraft industry because the thin thickness and large size of the components make it difficult to control the tolerance. “Weld ability of material”, “skin geometry” and “stringer geometry” were chosen by 75% of interviewees or more, as skin-stringer joint design considerations. Only 2 and 1 have chosen the “skin manufacturing method” and “stringer manufacturing method” respectively. Because most stringers have a standard profile and skins are stretched or chemically milled. This is common sense in aircraft industry. However, when DFMA should be applied, the manufacturing methods of the design component must be considered. Thus, this should be an issue in COMAC and needs to be improved. The answers to question L7 are illustrated in Figure 5-4 in detail.


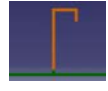



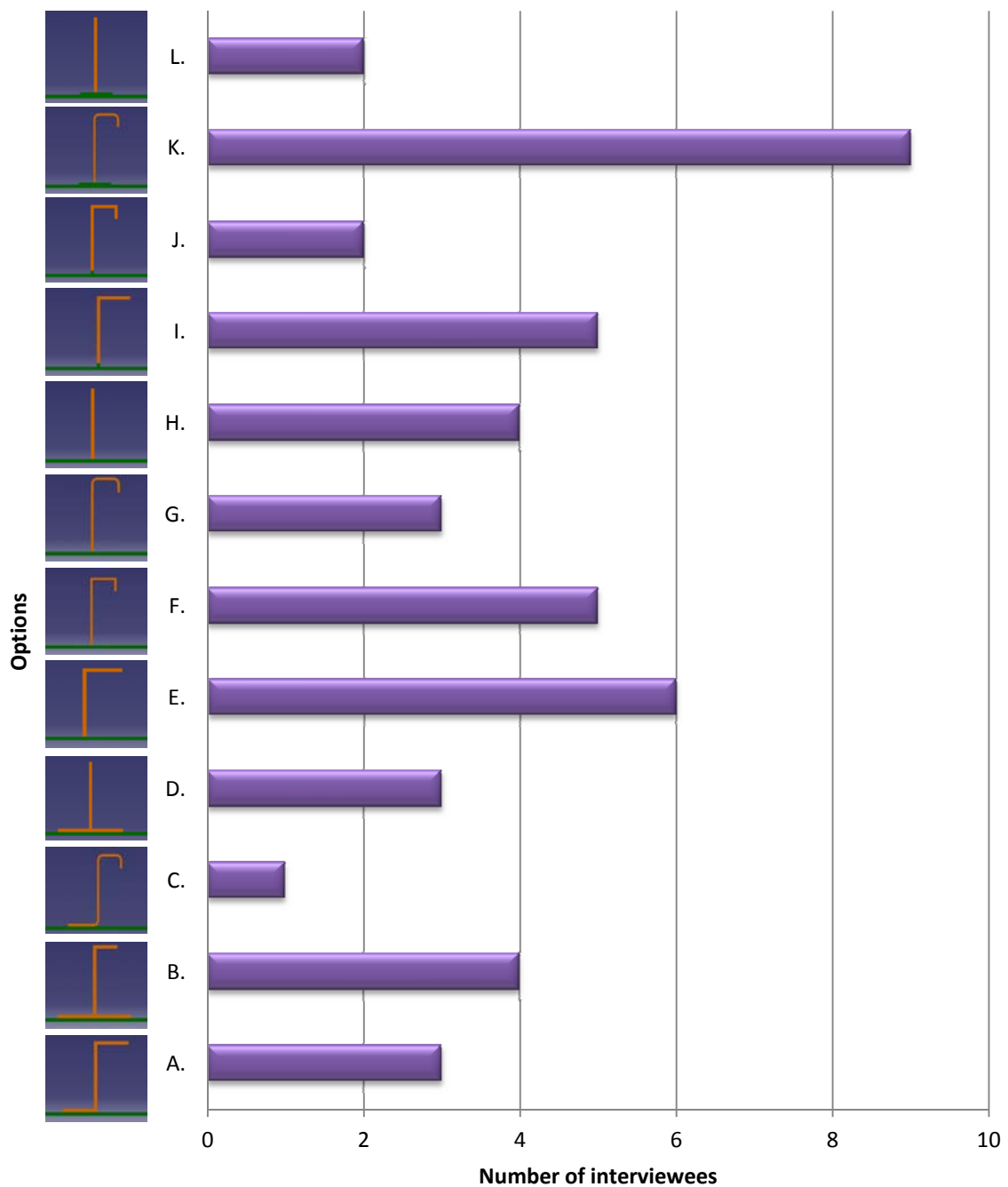
**L8. Which of the following joint types will you choose for LBW in the aircraft industry? ( You can choose four options at most )**

Nine interviewees have chosen a joint constructed with various thicknesses of

skin and a formed stringer with riveting strap eliminated  , while interviewees have chosen a joint type built up with an extrusion stringer with

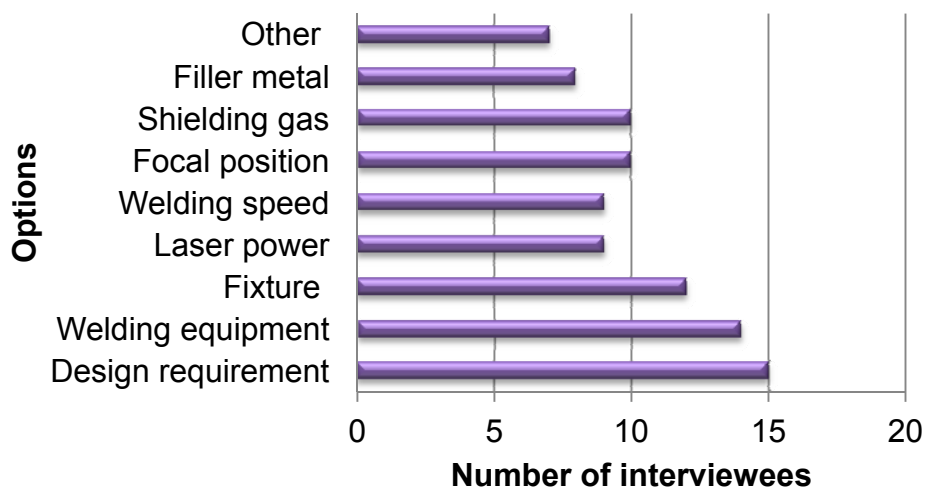
riveting strap eliminated and uniform thickness skin  . Only 1 has chosen

the conventional joint type which was always used for riveting . Other choices are illustrated in the following bar chart. The joint type  for stringer-skin and  for clip-skin which were recommended in the literature were not widely supported by the interviewees, only receiving 2 votes each. The main reason could be the weight reduction when comparing a formed stringer to an extruded stringer.



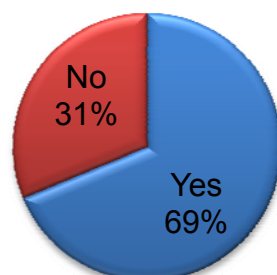
**L9. What should be taken into account when planning the LBW process?  
(You can choose as many options as you wish)**

12-15 (75%-94%) interviewees considered “Design requirement”, “Welding equipment” and “Fixture” as process planning considerations, while 8-10(50%-63%) chose process parameters such as “focal position”, “shielding gas”, “laser power”, “welding speed” and “filler metal”. 7 interviewees have suggested other aspects, such as “pre-welding preparation”, “post-welding treatment” and also “the design of the welding head” as this will influence the feeding method of the filler.



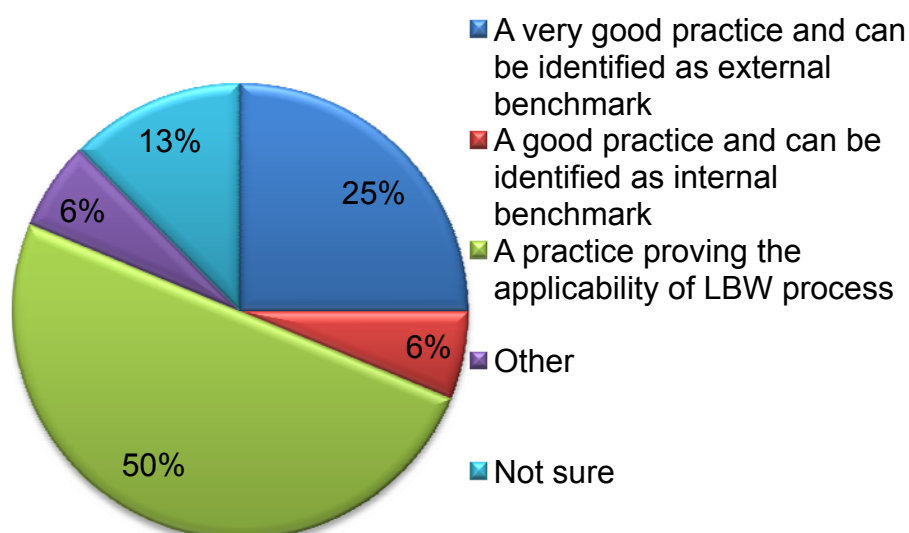
**L10. The LBW process has already been applied to the manufacturing of fuselage panels of Airbus A318, A340 and A380. Did you know about it?**

11 (69%) interviewees knew about the application of the LBW process in Airbus A318, A340 and A380, while the other 5 did not. The main sources of this information are A380 official reports and other technical papers from co-operators of Airbus who have been involved in the innovation of the LBW process for fuselage panels.



**L11. What do you think about the application of the LBW process in Airbus?  
(Choose the most suitable option)**

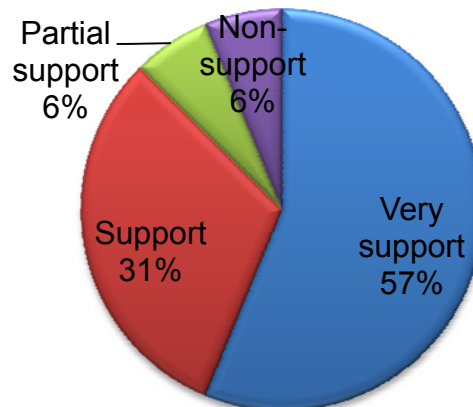
8 (50%) interviewees thought the application of the LBW process in Airbus was simply a practice, i.e. just providing the applicability of the LBW process, because they thought the advantages of this technology still need time to be proved. 4 (25%) interviewees were optimistic and considered it to be “a very good practice and can be identified as external benchmark”, because they thought the application of the LBW process in Airbus is not only for the skin-stringer, but also for skin, clip, frame and seat rail, which have been proved to be an excellent application in the aircraft industry. Only 1 interviewee has chosen “a good practice as internal benchmark” and “other” while 2 interviewees were not sure about it.



**L12. What is your attitude to developing LBW process capabilities and applying the LBW process in the aircraft industry?**

9 (57%) interviewees chose “very support” and 5 (31%) chose “support” for developing LBW process capabilities and applying the LBW process in the aircraft industry as they thought LBW could fabricate fuselage panels with lighter weight, higher efficiency, lower operation cost, and without loss of strength. They are optimistic about the perspective of the LBW process. Some interviewees also thought it would promote the development of aircraft structure and the LBW process itself. A small number of interviewees did not support it because they

thought that its successful application in the aircraft industry is not enough and they were concerned about the strength and quality of the welds.

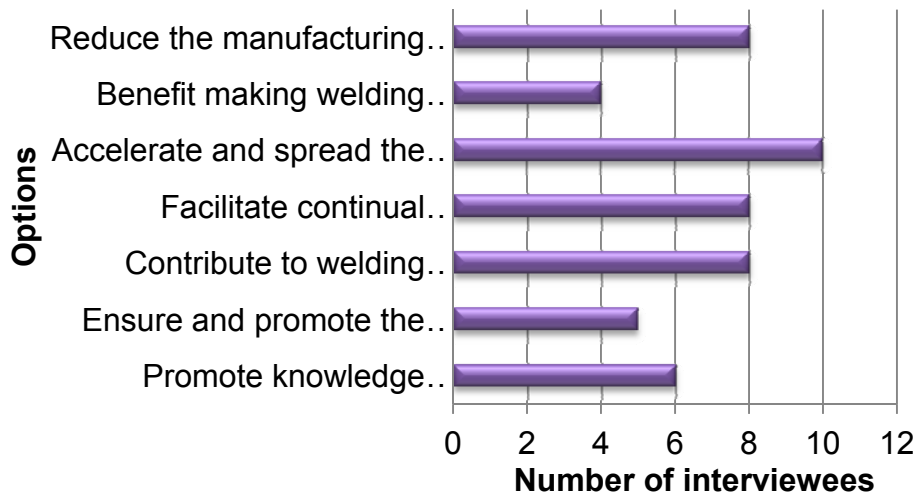


### **B.3 Capturing the Laser Beam Welding process capabilities**

**K1. From your experience, what are the most important benefits of capturing the LBW process capabilities in the aircraft industry? (You can choose four options at most)**

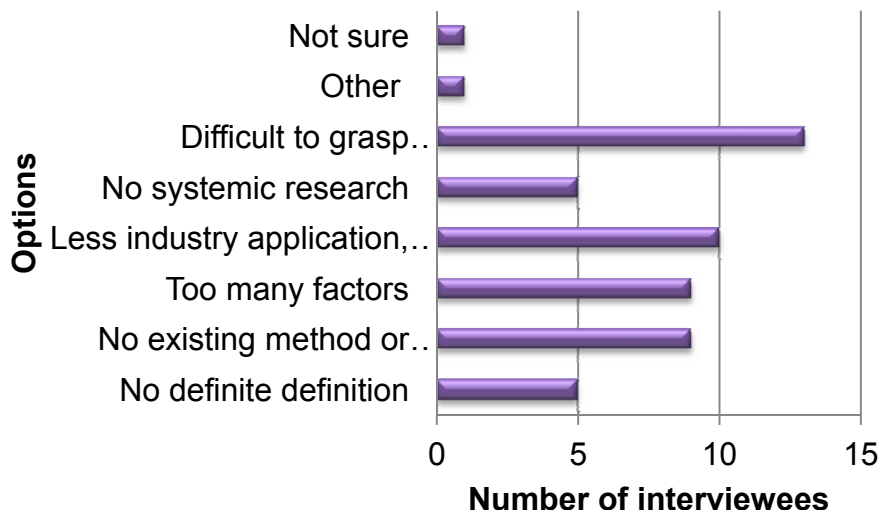
For the benefits of capturing the LBW process capabilities in the aircraft industry, the most chosen option was “Accelerate and spread the application of LBW process”, which was chosen by 10 (63%) interviewees and was in line with the aim of this project. Three options, namely “Contribute to welding structure design”, “Facilitate continual improvement of LBW process capabilities” and “Reduce the manufacturing cost of a certain component” took second place, each option was chosen by 8 (50%) interviewees. “Promote knowledge management of LBW process”, “Ensure and promote LBW process capabilities” and “Benefit making welding strategy” were chosen by 6 (38%), 5 (31%) and 4 (25%) interviewees respectively.





**K2. Which do you think are the difficulties of capturing the LBW process capabilities? (You can choose four options at most)**

The option “Difficult to grasp comprehensive data for secrecy reasons” was chosen by 13 (81%) interviewees as the difficulties of capturing the LBW process capabilities. “Less industry application”, “No existing method or procedure” and “Too many factors” were chosen by 10 (63%), 9 (56%) and 9 (56%) interviewees respectively. 5 (31%) chose “No definite definition” and “No systemic research”. Some interviewees thought the restrictions from welding equipment also brought difficulties.



**K3. Do you think it is necessary to capture the LBW process capabilities?**

**(‘Yes’ or ‘No’) Please give your reasons from your experience, if possible.**

All the interviewees thought it necessary to capture the LBW process capabilities although the reasons given were different. Some interviewees thought it would help to further understand the LBW process and its influencing factors, implement LBW research and improve the structure design strategy. Others thought it would provide an optional joining technology for COMAC, and improve both competitiveness and the manufacturing capabilities.

**K4. Please write down any words you would like to give this project.  
(Suggestion or comment)**

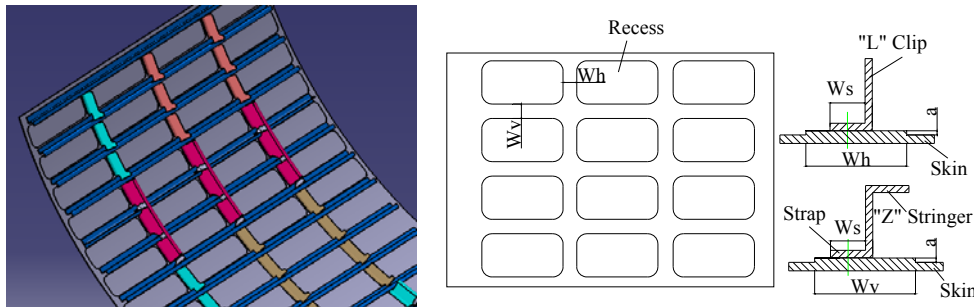
Most interviewees were concerned about the application of the results of this research project, i.e. a systemic report with some case study and testing components were expected and suggested in order to validate the rules and recommendations and help those who wish to apply LBW to industry application. A series of Process Specifications and quality assessment systems were also suggested in order to help extend the application of LBW. Some interviewees even wished that Airbus could push and extend the global application of the LBW process.

## Appendix C Questions and answers of interviews

**Q1.** What is the recommended range of skin thickness for fuselage panel?  
What about low fuselage panel?

**Answer1.** The minimum skin thickness is 1.2mm and the common thickness range of low fuselage panel is 1.4mm - 2.2mm.

**Q2.** For chemical milling skin, is there any rule of thumb for the value of  $W_h$  and  $W_v$ , which is the strap width on the skin in horizontal and vertical direction respectively?

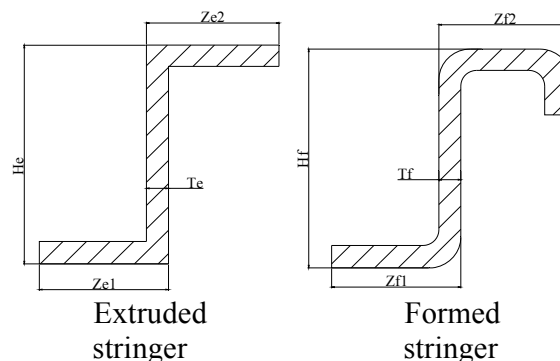


**Answer2.** The milling aspect ratio is 0.9-1.3 and the strap width on the skin is determined by the strap on the stringer and clip.

**Q3.** For chemical milling skin, what tolerance is usually given in the design stage? And are there any rules?

**Answer3.** The common tolerance for chemical milling skin is 0.08mm in the skin thickness direction and  $\pm 0.5$ mm in width direction.

**Q4.** What is the recommended stringer structure (cross section) in an aircraft fuselage panel? ( $H_e$ ,  $Z_{e1}$ ,  $Z_{e2}$  and  $T_e$  for extruded stringer and  $H_f$ ,  $Z_{f1}$ ,  $Z_{f2}$  and  $T_f$  for formed stringer)



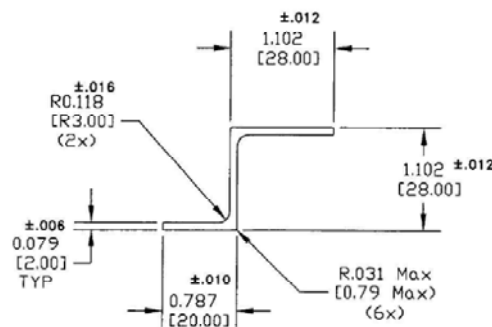
**Answer4.** The usual chosen structure is extruded stringer. And the dimensions are  $H_e=28$ mm,  $Z_{e1}=20$ mm,  $Z_{e2}=28$ mm and  $T_e=2$ mm.

**Q5.** What type of stringer is preferred, a formed stringer or an extruded one?  
How to choose them?

**Answer5.** Most stringer structures use a standard extruded profile except some non standard structures, which are formed with aluminium sheet metal by the aircraft manufacturing company itself.

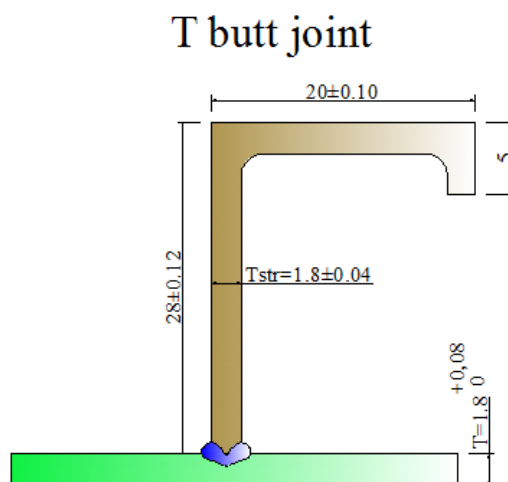
**Q6.** For stringers, what tolerance is usually given in the design stage? And are there any rules?

**Answer6.** Reference to the AA material specification.



**Q7.** If the traditional riveting process is substituted by an LBW process, what influence will be brought to the above design considerations?

**Answer7.** The stringer structure will be changed as follows:



**Q8.** How to conduct LBW process planning? What should be done in this stage?

**Answer8.** Choose LBW equipment, define the procedure, choose process parameters, performance testing (specimen, typical parts and analogue parts) and verification experiments

**Q9.** How to verify that the whole LBW procedure is under control? What are the vehicles?

**Answer9.** Define process specification and make sure it is followed during the whole welding procedure. It will ensure that the process is under control.

**Q10.** How to keep the workpiece and filler metal in a good welding condition and make sure they won't cause additional weld defects.

**Answer10.** Firstly, the feeding should be stable; secondly, the filler position, feeding speed should be controlled to reduce the existence of jump wire and sticky wire and to prevent defects such as undercut, partial penetrated welding, cracking and pores.

**Q11.** How to verify that the operator is qualified to conduct LBW?

**Answer11.** Complete theoretic and practical training, a relative certificate should be obtained before conducting LBW

**Q12.** How can we know that the product fabricated with the LBW process meets the quality requirement? Whether a quality control plan is needed? If needed, what should be contained in the plan?

**Answer12.** A complete quality assessment system and specification should be established; assess the welding product following the specification strictly, Refer to AWS D17.1 Specification for Fusion Welding of Aerospace Applications for detailed information.

**Q13.** What should be considered when designing the fixture for the LBW process for the aircraft fuselage panel?

**Answer13.** The fuselage panel welding fixture can be divided into two parts. One is for skin location and clamping, and the other for stringer location and clamping. The skin fixture should provide an accurate location of the skin as well as thermal uniformity to prevent deformation. The stringer fixture should eliminate the gap between skin, and stringer and guide the stringer accurately. Simultaneously, the work head of the fixture should be flexible, so that with a welding panel with curvature, the motion statue could change with the curvature freely.

**Q14.** How to locate and clamp the skin? How to define the fixture tolerance?

**Answer14.** Full-surface vacuum fixture can be used for skin location and clamping.

**Q15.** How to locate and clamp the stringer? How to define tolerance?

**Answer15.** The LBW equipment should have special stringer location and clamping work head for locating and guiding the stringer. It is commonly constructed with a guiding and clamping roller. For a single panel, the stringer fixture just needs an X-Y-Z three axes linkage. For a hyperbolic panel, the stringer fixture needs 5 axes linkage at least.

**Q16.** Which type of fixture is preferred, a simple fixture fabricated with sheet metals, a strong fixture welded with profile, or a flexible fixture and why?



A: simple welded fixture    B: strong welded fixture    C: flexible fixture

**Answer16.** B type fixture is pretty good as the full-surface vacuum fixture can not only ensure accuracy, but also provide thermal uniformity to reduce deformation.

**Q17.** What materials are preferred for fixture used for fuselage panel fabrication with LBW and why?

**Answer17.** The fixture shall be made from materials that will not affect the weld or base metal quality through contact. However, the initial choice is aluminium as it is convenient to be fabricated and the thermal expansion coefficient is the same as the workpiece to improve the cooling effect.

## Appendix D Rules and Recommendations Set for Laser Beam Welding in the aircraft industry

Introduction
<p>These rules and recommendations focus on the design of skin and stringer structures and the effect of process parameters on as-welded geometry as well as fixture design considerations. The aimed structure is a T butt joint made of aluminium alloy and with a thin thickness (Typically: 1.8<sub>mm</sub>). Some terms and definitions are introduced as follows:</p> <p><b>Laser power (P):</b> the output power rate of laser equipment, expressed as “KW” as example.</p> <p><b>Welding speed (V<sub>w</sub>):</b> the relative motion between the laser beam and the workpiece, expressed as “m/min” as example.</p> <p><b>Feeding speed (V<sub>f</sub>):</b> the output rate of filler metal, expressed as “m/min” as example.</p> <p><b>Incident position (d):</b> the place of the focal spot on the workpiece which can be represented by the distance from the focal spot to the skin surface, expressed as “mm” as example.</p> <p><b>Incident angle (θ):</b> the angle between the optical axis of the incident laser beam and the normal to the workpiece, expressed as “deg” as example.</p> <p><b>Spot size (D):</b> the diameter of a focused laser beam, expressed as “mm” as example.</p> <p><b>Spot area (A):</b> the area of focal spot, expressed as “cm<sup>2</sup>” as example.</p> $A = \frac{1}{4} \pi D^2$ <p><b>Power density (I):</b> intensity or the power per unit area of the output of a laser, expressed as “W/cm<sup>2</sup>” as example.</p> $I = P/A$ <p><b>Linear heat input (E’):</b> the energy put onto the workpiece per unit length, expressed as “J/mm” as example.</p> $E' = P/V_w$ <p><b>Heat source clearance (a):</b> the distance between the focal spots of two lasers in dual beam welding in the direction of V<sub>w</sub>, expressed as “mm” as example.</p>

**Filler position (b):** the distance between the end of the filler metal and the focal spot, expressed as “mm” as example.

Other terms include:

$V_g$ : shielding gas flow rate;  $T$ : skin thickness;  $T_{str}$ : stringer thickness;

The LBW process of skin-stringer connection is schematically illustrated in Figure D-1; most process parameters are shown in this diagram.

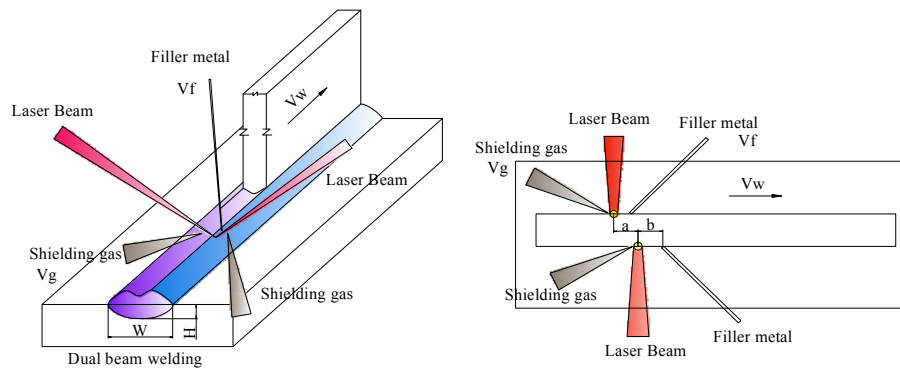


Figure D-1 Schematic diagram of Laser Beam Welding of T butt joint

The as-weld geometry is illustrated in Figure D-2, includes five main parameters:  $H$  for weld depth,  $W$  for weld width,  $\gamma$  for angle of weld profile, “ $\delta$ ” for deformation and “ $\phi$ ” for angular distortion.

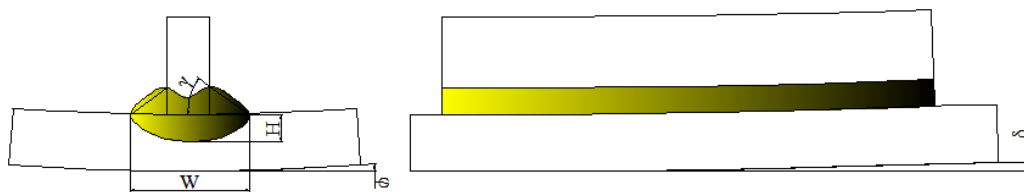
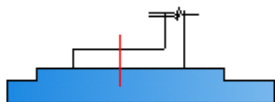
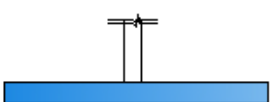
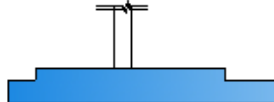
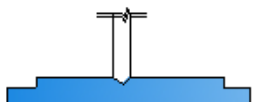
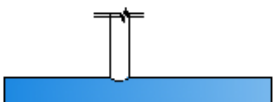
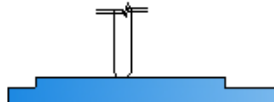
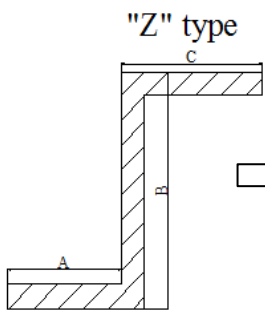
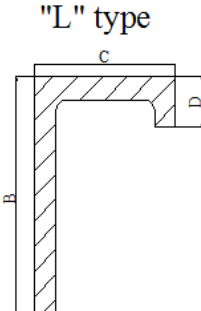
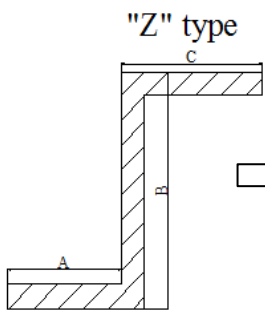
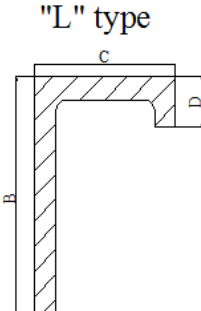
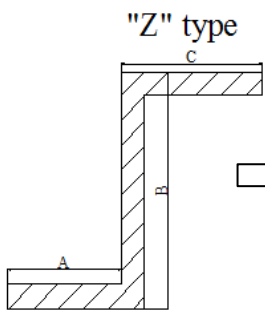
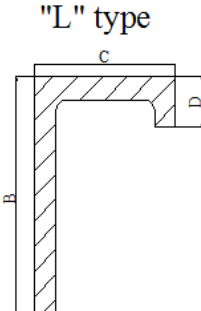


Figure D-2 Schematic diagram of as-welded geometry



D.1 Rules and Recommendations for Structure Design

SDRR.1	Product								
SDRR.1.1	Geometry								
1) "Accessibility of the laser beam to the joint as well as space for fixture/tooling must be considered when designing structure for LBW."									
2) "T butt joint is recommended for skin-stringer connection to achieve potential weight reduction"									
<div><div><p>Riveting, lap or lap edge welding</p></div><div><p>T butt welding with uniform skin thickness</p></div><div><p>T butt welding skin with steps</p></div><div><p>Both skin and stringer are triangular edge prepared</p></div><div><p>Both skin and stringer are trapeziform edge prepared</p></div><div><p>Only stringer is trapeziform edge prepared</p></div></div> <div><p>Figure D-3 Possible joint configurations for skin-stringer connection</p></div> <tr><td colspan="2">3) "'L" type stringer is recommended for Laser Beam Welded fuselage panel to form T butt weld and gain potential weight reduction"</td></tr> <tr><td colspan="2"><div><div><p>"Z" type</p></div><div><p>"L" type</p></div></div></td></tr> <tr><td colspan="2">Figure D-4 The recommended stringer geometry for Laser Beam Welding</td></tr> <tr><td colspan="2">4) "Feathers for skin location should be set on the skin, and holes for location are recommended"</td></tr>		3) "'L" type stringer is recommended for Laser Beam Welded fuselage panel to form T butt weld and gain potential weight reduction"		<div><div><p>"Z" type</p></div><div><p>"L" type</p></div></div>		Figure D-4 The recommended stringer geometry for Laser Beam Welding		4) "Feathers for skin location should be set on the skin, and holes for location are recommended"	
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<div><div><p>"Z" type</p></div><div><p>"L" type</p></div></div>									
Figure D-4 The recommended stringer geometry for Laser Beam Welding									
4) "Feathers for skin location should be set on the skin, and holes for location are recommended"									

## SDRR.1.2 Dimension

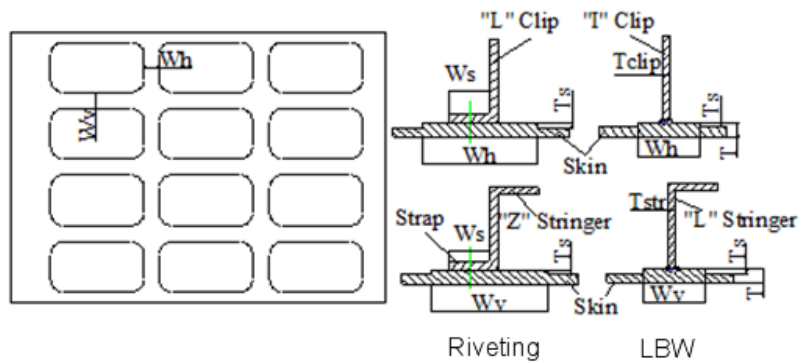


Figure D-5 Schematic diagram of skin geometry with recess

$W_h$ : Width of steps on the skin in horizontal direction;

$W_v$ : Width of steps on the skin in vertical direction;

$W_s$ : Width of strap on clip or stringer (a typical value=20<sub>mm</sub>);

- 5) "The thickness for low fuselage ranges from 1.4<sub>mm</sub> to 2.2<sub>mm</sub>, depending on the strength requirement. The recommended value is 1.8<sub>mm</sub>."
- 6) If (recesses are designed on the skin for weight reduction) then "The step width on the skin can be calculated as:  $W_v = W_s \text{ (stringer)} + 10_{\text{mm}}$  and  $W_h = W_s \text{ (clip)} + 10_{\text{mm}}$ "

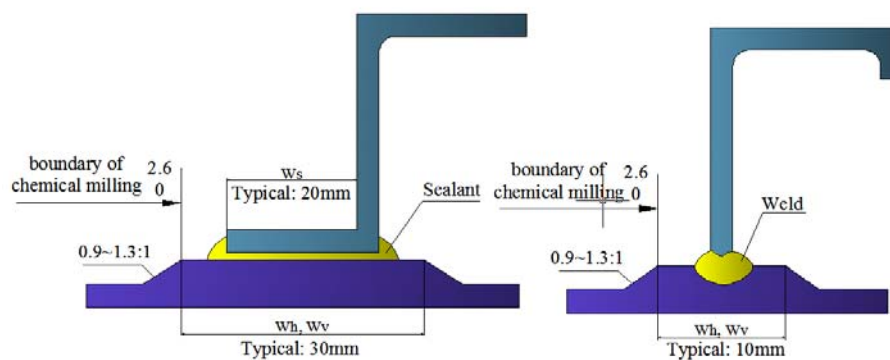


Figure D-6 Schematic diagram of step width on the skin

- 7) "The recommended weld depth (H) is about 0.5 x skin thickness (T), and the suggested angle of weld profile ( $\gamma$ ) is 45°"

### SDRR.1.3 Tolerance

8) If (the Gap  $\leq 10\%$  x the sheet thickness(T)) then “the weld is properly stable”

Else if ( $10\%T < \text{Gap} \leq 20\%T$ ) then “ the weld becomes unstable”

Else if(Gap  $> 20\%T$ ) then “the weld cannot be finished”

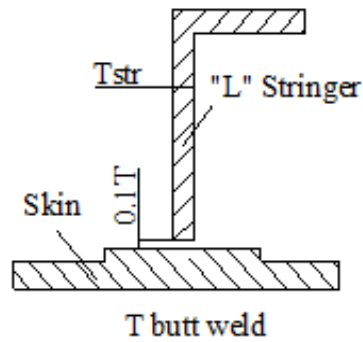


Figure D-7 Schematic diagram of gap for T butt joint

## D.2 Rules and Recommendations for Process Planning

<b>PPRR.1 Process</b>
<b>PPRR.1.1 Procedure</b>
<p>1) “Dual beam welding with two CO<sub>2</sub> lasers are recommended for skin-stringer T butt joint”</p> <p>2) “The process must be performed under Process Specification which has been validated in the industry environment”</p>
<b>PPRR.1.2 Laser power</b>
<p>3) If (<math>P \leq P_1</math>) then “the weld pools at two sides of the T butt joint separate, which results in low joint strength”</p> <p>Else if (<math>P_1 &lt; P &lt; P_2</math> and <math>P \uparrow</math>) then “weld width (<math>W</math>) <math>\uparrow</math>, weld depth (<math>H</math>) <math>\uparrow</math>, angle of weld profile (<math>\gamma</math>) <math>\downarrow</math>, angular distortion (<math>\phi</math>) <math>\uparrow</math>, deflection (<math>\delta</math>) <math>\uparrow</math>”</p> <p>Else if (<math>P \geq P_2</math>) then “the skin is fully penetrated which induces the risk of sealing and dropout”</p> <p>Where <math>P_1</math> is the critical power that makes the two weld pools of two sides of the T butt joint join together and <math>P_2</math> is the critical power that makes full penetration of the skin. These two critical powers are not constant in different conditions.</p> <div data-bbox="295 1361 1316 1780" data-label="Figure"> <p>The diagram illustrates the relationship between laser power (<math>P</math>) and the weld profile of a skin-stringer T butt joint. It features a cross-sectional view of the joint at the top, showing the skin and stringer components. Below this, a horizontal axis represents the laser power (<math>P</math>), with two critical points marked: <math>P_1</math> and <math>P_2</math>. The region between <math>P_1</math> and <math>P_2</math> is labeled 'Incomplete joining of skin-stringer', while the region beyond <math>P_2</math> is labeled 'Full penetration of skin'. A weld profile is shown as a dashed line within the joint, with parameters <math>W</math> (weld width), <math>H</math> (weld depth), <math>\gamma</math> (angle of weld profile), <math>\phi</math> (angular distortion), and <math>\delta</math> (deflection) indicated. The text 'laser power (<math>P</math>) increase' is written above the diagram, and an arrow points to the right along the power axis.</p> </div>

Figure D-8 Effect of laser power on weld profile

### Heat source clearance (a)

- 4) If  $(a \uparrow)$  then " $W \uparrow$  slightly,  $H \downarrow$  slightly,  $\gamma \downarrow$ ,  $\delta \downarrow$ ,  $\phi \downarrow$ "  
Else " $W \downarrow$  slightly,  $H \uparrow$  slightly,  $\gamma \uparrow$ ,  $\delta \uparrow$ ,  $\phi \uparrow$ "

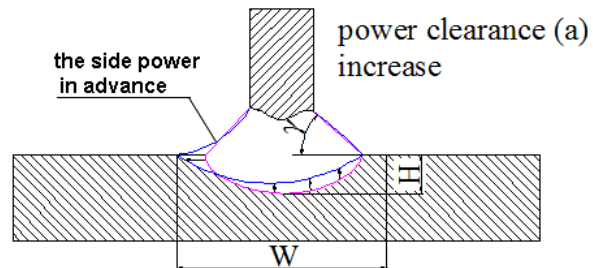


Figure D-9 Effect of heat source clearance on weld profile

### PPRR.1.3 Focal position

#### The incident angle of laser beam ( $\theta$ )

- 5) If  $(\theta \uparrow)$  then " $W \uparrow$ ,  $H \uparrow$ ,  $\gamma \downarrow$ ,  $\delta \uparrow$ ,  $\phi \uparrow$ "  
Else if " $W \downarrow$ ,  $H \downarrow$ ,  $\gamma \uparrow$ ,  $\delta \downarrow$ ,  $\phi \downarrow$ "

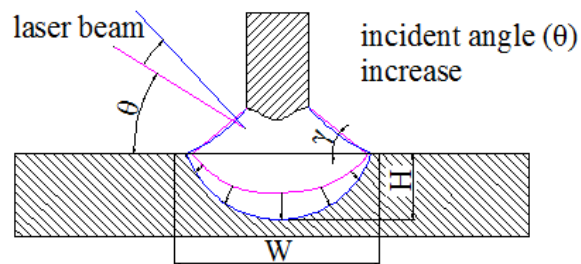


Figure D-10 Effect of incident angle on weld profile

### The incident position of laser beam (d)

6) If ( $d \uparrow$ ) then " $W \downarrow, H \downarrow, \gamma \uparrow, \delta \downarrow, \phi \downarrow$ "

Else " $W$  and  $H \uparrow, \gamma \downarrow, \delta \uparrow, \phi \uparrow$ "

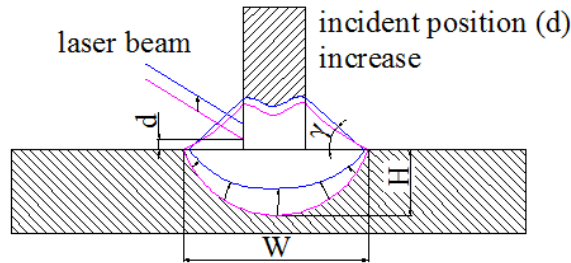


Figure D-11 Effect of incident position on weld profile

### PPRR.1.4 Welding speed ( $V_w$ )

7) If ( $V_w \leq V_{w1}$ ) then "skin is likely to be fully penetrated"

Else if ( $V_{w1} < V_w < V_{w2}$  and  $V_w \uparrow$ ) then " $W \downarrow, H \downarrow, \gamma \uparrow, \delta \downarrow, \phi \downarrow$ "

Else if ( $V_w \geq V_{w2}$ ) then "undercut is likely to exist because of short of filler metal"

Else if ( $V_w \geq V_{w2}$ ,  $V_f/V_w$  keeps constant and  $V_w \uparrow$ ) then " $W \downarrow, H \downarrow, \gamma \uparrow, \delta \downarrow, \phi \downarrow$ "

Where  $V_{w1}$  is the critical welding speed that makes full penetration of skin in certain conditions and  $V_{w2}$  is the critical welding speed that results in undercut from shortage of filler metal.

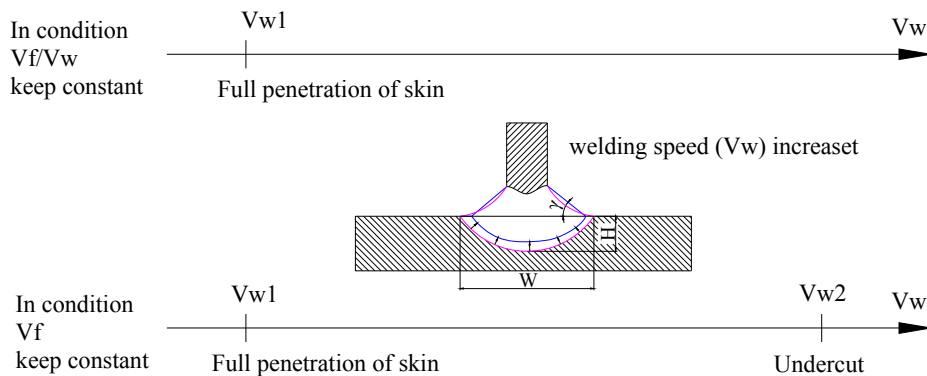


Figure D-12 Effect of welding speed on weld profile

### PPRR.1.5 Filler metal

#### Filler type

- 8) “An Aluminium-Silicon filler metal, such as 4043 is recommended for improved corrosion resistance when welding alloy 6061 base metal.”

#### Filler position (b)

- 9) If (the spot size ( $D$ ) =  $0.9\text{mm}$ , the diameter of filler metal ( $D_f$ ) =  $1\text{mm}$  and  $b \leq 1.5\text{mm}$ ) then “The welding with filler can be accomplished properly, the weld is fairly good.”

Else if ( $D = 0.9\text{mm}$ ,  $D_f = 1\text{mm}$  and  $b > 1.5\text{mm}$ ) then “The welding cannot be accomplished with good welds.”

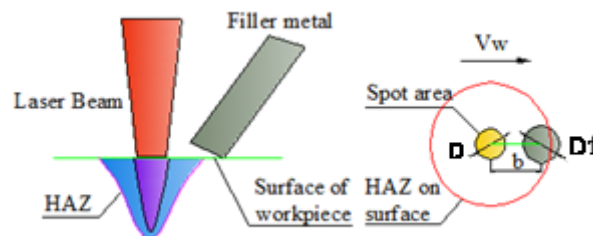


Figure D-13 Schematic diagram of filler position

#### Feeding speed ( $V_f$ )

- 10) If(  $V_f \uparrow$  and  $V_w$  keep constant) then “ $W \uparrow$ ,  $H \downarrow$ ,  $\gamma \uparrow$ ,  $\delta \downarrow$ ,  $\phi \downarrow$ ”

Else if (  $V_f \uparrow$  and  $V_f/V_w$  keep constant) “ $W \downarrow$ ,  $H \downarrow$ ,  $\gamma \uparrow$ ,  $\delta \downarrow$ ,  $\phi \downarrow$ ”

### PPRR.1.6 Shielding gas

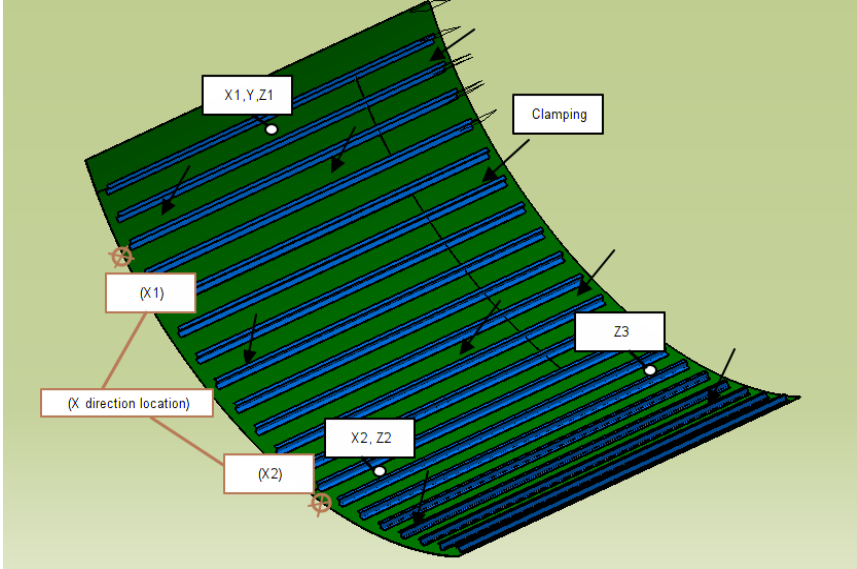
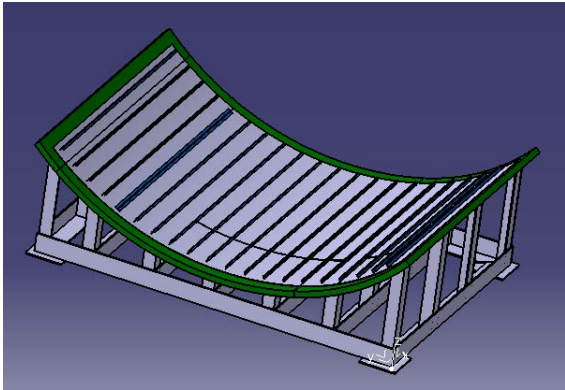
- 11) “Argon, helium and Ar/He mix are all acceptable for LBW of Aluminium.”

- 12) “Pure helium or Ar/He mix is recommended for  $\text{CO}_2$  laser to suppress plume.”

### PPRR.1.7 Joint preparation

- 13) “Contaminants such as moisture, dust and lubricants near the welding area should be eliminated to make sure the workpiece is clean and dry.”

- 14) “Dull and unpolished surfaces are preferred for LBW.”

<b>PPRR.2</b>	<b>Resource</b>
<b>PPRR.2.1</b>	<b>Fixture</b>
<p>15) “Fixture/tooling structure must allow for beam access and gas shielding.”</p> <p>16) “The choice of feathers for location should follow the principle “location hole&gt; skin surface&gt;skin boundary” for accuracy issues.”</p>	
 <p>Figure D-14 A typical location system with three location holes</p>	
<p>17) “It is recommended to clamp the skin at multiple places in order to keep skin geometry during processing.”</p> <p>18) “Full-surface vacuum fixture is a recommended solution for skin location and clamping because it ensures the accuracy and provides thermal uniformity to reduce deformation.”</p>	
 <p>Figure D-15 An example of a simple full-surface fixture</p>	



- 19) "The recommended location plane for stringers are the inside surface of the skin and the side planes A and C of the stringer."

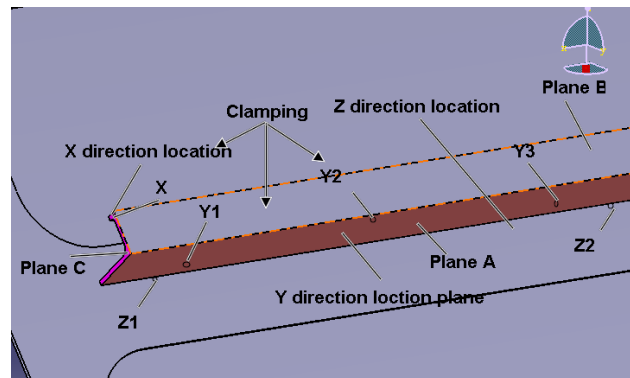


Figure D-16 A basic location system for stringer

- 20) "A stringer guiding system fixed with the working head is recommended in order to keep locate the stringer accurately as well as prevent influence to path of laser beam."

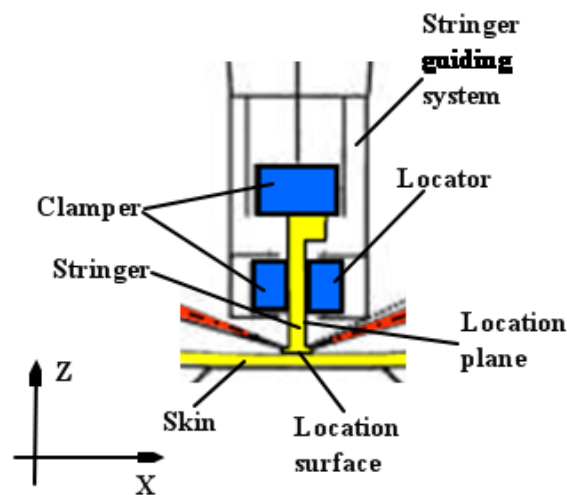


Figure D-17 Schematic diagram of stringer guiding system(Rendigs and knower, 2010)

# **Appendix E    Prototype    of    Laser    Beam    Welding handbook for aircraft fuselage panel development**

## **Content of prototype of handbook**

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## E.1. Introduction

The typical semi-monocoque structure for aircraft fuselage panel is illustrated in Figure E-1, building up with skin, stringer, clip, frame and other elements according to different joining methods, such as rivets and sealant for riveting, and filler materials for welding.

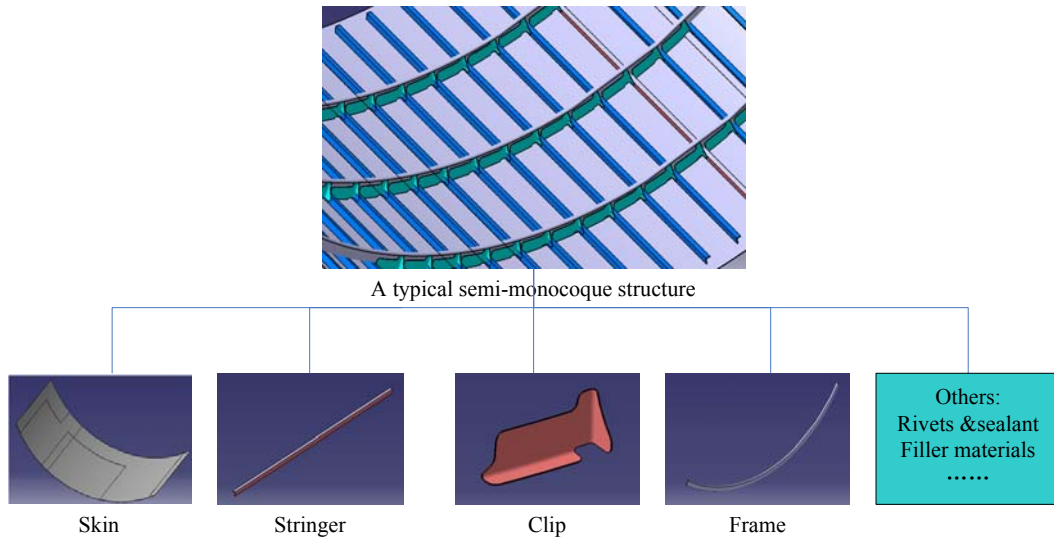


Figure E-1 A typical semi-monocoque fuselage panel structure composition

The traditional joining method for this structure is riveting, but studies show that the LBW process can provide a great potential for weight reduction, which is attractive for the aircraft industry. The idea of applying LBW in the aircraft industry was first raised in Russia in 1989 for skin-stringer joining and the first production shell was approved in 2001 for the A318. Up to 2010, more than 1200 shells for the A318, A340 and A380 have been produced (Rendigs and knower, 2010), which has proved LBW a reliable process in this industry. The application in Airbus demonstrates a 5% to 10% weight reduction of the panel structure weight and has led to a migration from riveting to LBW for metal fuselage fabrication.

This handbook is intended to give a basic introduction and guidelines to those who intend to apply the LBW process to aircraft fuselage panel fabrication. It focuses on the design of skin and stringer structures as well as the principles for process parameter selection and fixture design. These basic guidelines are

represented as rules and recommendations and can also be retrieved and applied to other joints, such as skin-clip joining.

## E.2. Terms and definitions

**Laser power (P):** the output power rate of laser equipment, expressed as “KW”.

**Heat source clearance (a):** the distance between the two focal spots along the direction of welding speed in dual beam welding, expressed as “mm”.

**Welding speed ( $V_w$ ):** the relative motion between the laser beam and the workpiece, expressed as “m/min”.

**Feeding speed ( $V_f$ ):** the output rate of filler metal, expressed as “m/min”.

**Incident position (d):** the position of focal spot on the workpiece which can be represented by the distance from the focal spot to the skin surface, expressed as “mm”.

**Incident angle ( $\theta$ ):** the angle between the optical axis of the incident laser beam and the normal to the workpiece. A perpendicular angle is most often used, expressed as “deg”.

**Spot size (D):** the diameter of a focused laser beam, expressed as “mm”.

**Spot area (A):** the area of focal spot, expressed as “cm<sup>2</sup>”.

$$A = \frac{1}{4} \pi D^2$$

**Power density (I):** intensity or the power per unit area of the output of a laser, expressed as “W/cm<sup>2</sup>”.

$$I = P/A$$

**Linear energy input (E’):** the energy put into the workpiece per unit length, expressed as “J/mm”.

$$E' = P/V_w$$

**Conduction mode welding:** a melting and fusing operation in which the incident beam energy is transferred to the root of the weld solely by conductive and convective heat flow in the molten metal.

**Keyhole mode welding:** a technique that employs a concentrated heat source with sufficient intensity to vaporize some workpiece material. This results in the formation of a vapour hole (keyhole), which is surrounded by molten material that penetrates deeply into or through the workpiece. As the concentrated heat is advanced, molten metal flows around the walls of keyhole, fills in the trailing edge, and solidifies to produce a continuous weld.

### E.3. Principle of Laser Beam Welding

Laser beam welding is a fusion welding process that results in the joining of materials by the interaction of a concentrated beam of light and the material surface. The temperature created by this interaction is sufficient to produce melting or even vaporization of the material and joining of the molten material from the workpiece being welded. The principle of LBW is presented in Figure 2-4 according to Behler et al. (1997).

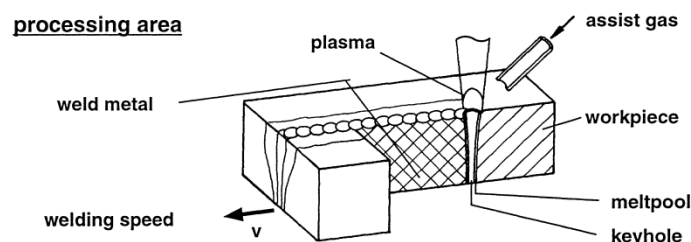


Figure E-2 Principle of Laser Beam Welding (Behler et al. 1997)

There are two distinctly different modes of LBW which are commonly referred to as conduction mode welding and keyhole mode welding (Duley, 1998; AWS, 2010); and LBW can be classified as single beam welding, dual beam welding and Laser-X hybrid welding (X is a different welding method) depending on the different energy sources. A brief introduction to LBW is illustrated in Figure E-3.

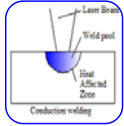
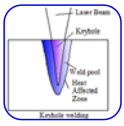
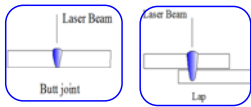
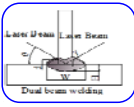
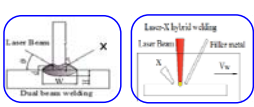
Laser beam welding			
Two modes	Conduction welding		Keyhole welding
	 <ul style="list-style-type: none"> <li>• Low power density</li> <li>• Aspect ratio 0.5-1.0</li> </ul>	 <ul style="list-style-type: none"> <li>• High power density</li> <li>• Aspect ratio 1-10</li> </ul>	
Three methods	Single beam welding	Dual beam welding	Laser-X hybrid welding
	 <ul style="list-style-type: none"> <li>• Suit for butt &amp; tap joint</li> <li>• High accessibility</li> </ul>	 <ul style="list-style-type: none"> <li>• Symmetric welding</li> <li>• Suit for T butt joint</li> <li>• High accessibility</li> </ul>	 <ul style="list-style-type: none"> <li>• Asymmetric welding</li> <li>• limited accessibility</li> <li>• High cost</li> </ul>

Figure E-3 A brief introduction of Laser Beam Welding

For the **conduction welding** mode, as the power density is lower than the threshold density for penetration, the incident beam power on the surface is transferred to the root of the weld by conductive and convective heat flow in the molten metal. The maximum aspect ratio (weld depth divided by weld width) is low, commonly between 0.5 and 1.0 only. (AWS, 2010)

**Keyhole welding** occurs when the laser power density is greater than the threshold density. The material at the interaction point melts and vaporizes. Thus, the weld pool opens up to allow the laser beam to enter the melt pool and a deep cavity (Keyhole) is formed. The aspect ratio for keyhole welding could range from 1.0 to great than 10.0 (AWS, 2010). The threshold density is influenced by the material as well as the surface preparation.

For butt joint and lap joint, **single beam welding** is the common welding method as it is the simplest and most efficient one. However, for a T butt joint, **dual beam welding** is preferred because it will cause lower distortion. Single beam welding for this configuration easily causes residual stress and distortion. **Laser-X hybrid welding** combines the advantages of both welding

technologies because it introduces a secondary energy source to the weld pool area. For example, the Laser-Arc welding combines typical laser welding benefits—high travel speeds, limited HAZ and narrow weld joint—with those of arc welding, i.e. process energy efficiency and gap-bridging. The disadvantages are increased investment costs and limited accessibility which are brought with arc processes. (Green, 2005) This welding method can be applied to almost all the weld configurations.

#### **E.4. Advantages and disadvantages**

The advantages of the LBW process include:

- ✓ Potential weight reduction compared to the riveting process
- ✓ Narrow fusion and small HAZ, minimal shrinkage and distortion compared to the traditional welding process
- ✓ Good accessibility
- ✓ Fast welding speed up to 30 m/min which is suitable for batch production
- ✓ Welding dissimilar materials
- ✓ Atmosphere surrounded with shielding gas
- ✓ Preheat or post weld heat treatment may be eliminated
- ✓ Can be time shared among a number of work stations

Limitations of LBW process include:

- ✓ High cooling rates may cause cracking
- ✓ Vaporization of some alloys such as magnesium may cause strength reduction
- ✓ Thin sections require precision fixture and close fit-up tolerances
- ✓ Operator safety protection is required

#### **E.5. Applications in aircraft industry**

LBW offers the possibility to manufacture joints of almost all the light metals and their combinations, such as aluminium, magnesium and titanium, because of its high energy density. In the aircraft industry, LBW is preferred to the simple repeating and time consuming jobs, such as skin-stringer connection, because

LBW process is automotive and much faster than the traditional riveting process. The application of LBW in aircraft industry includes:

- ✓ Verified applications: low fuselage panel (skin-stringer, skin-clip) and inner flap panel
- ✓ Potential applications: up fuselage panel, floor rail etc.

## E.6. Structure design manual

It is important to first choose the right joint type to ensure that the structure design is suitable for LBW. Then the structure of the parts or components being welded as well as the material could be decided. When designing the structure, the tolerance should be considered carefully, as it is crucial to the welding quality in most conditions. Figure E-4 illustrates the formation of the structure design manual for LBW in the aircraft industry, including two aspects: structure and material. Two sample rules and recommendations about these aspects will be introduced in the sub-sections.

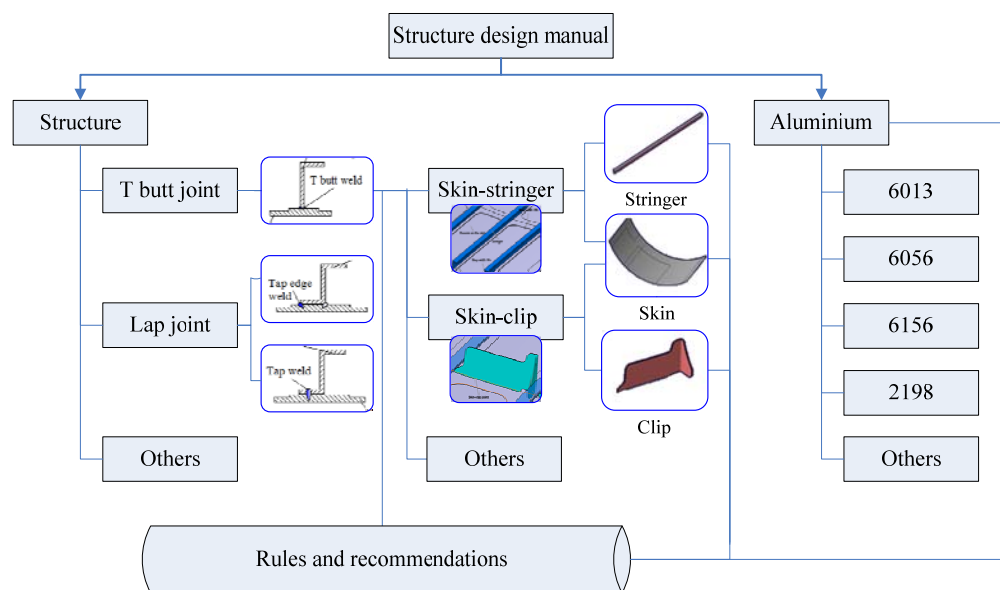


Figure E-4 Structure design manual for Laser Beam Welding in the aircraft industry



### E.6.1. Skin-stringer joint type recommendation

✚ “T butt joint is recommended for skin-stringer connection to achieve potential weight reduction”

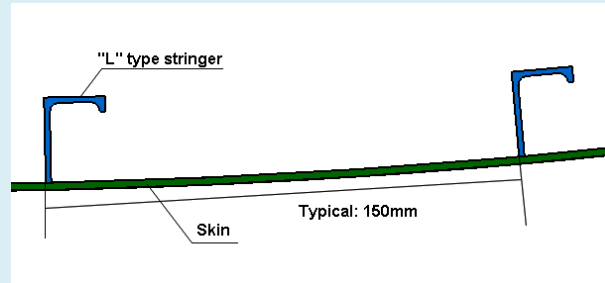


Figure E-5 A typical skin-stringer joint for Laser Beam Welding

The stringers are deposited perpendicularly to the skin at the required position, which is determined by the stringer axis provided by the upstream design stage. The T butt joint is recommended for LBW as it is possible to provide significant weight reduction through eliminating the strap on the stringer, and to avoid the risk of sealing and a sharp reduction of joining strength through full penetration on the stringer. All these advantages are what the tap weld and tap edge weld configurations can not provide.

According to different skin and stringer geometry as well as edge preparation, weld configurations can be various. Some of the possible configurations are illustrated in Figure E-6. The configurations with triangular or trapeziform edge preparation are not recommended because of induced difficulties with fabrication as well as increased production cost, although these configurations can improve weld properties. The T butt joint with no edge preparation is recommended for a skin-stringer connection.

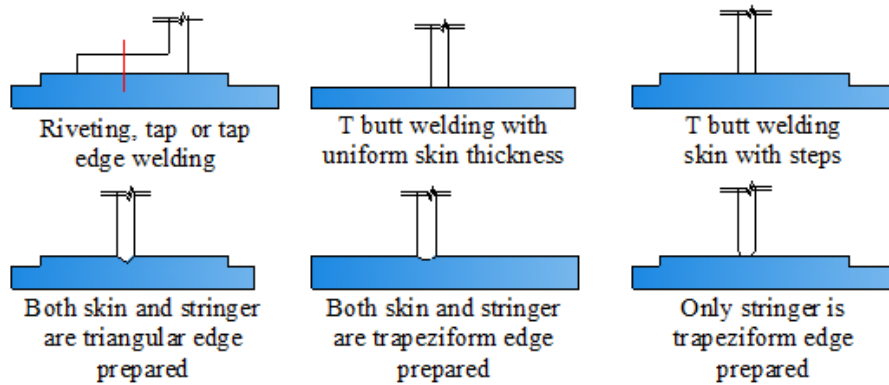


Figure E-6 Possible weld configurations for skin-stringer connection

### E.6.2. Stringer structure recommendation

“L” type stringer is recommended for Laser Beam Welded fuselage panel to form T butt joint”

The function of the stringer is to increase the longitudinal stability of the fuselage panel, and sustain the pressure together with skin, clip and frame. A “Z” type stringer is most commonly used for riveting, but a simplified “L” type stringer is recommended for LBW to form a T butt joint as illustrated in Figure E-7. Material with high strength as well as high notch toughness coupled with reasonable weldability is competitive for the stringer, e.g. 6056-T6.

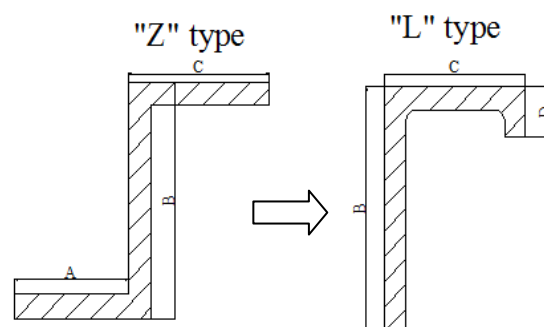


Figure E-7 Stringer structure recommendations for Laser Beam Welding

The “A” section of the traditional “Z” type stringer in Figure E-7 is eliminated for weight reduction to form T butt joint, whilst a “D” section is suggested to

compensate for the reduction of longitudinal buckling stability resulting from the elimination of the “A” section.

## E.7. Process planning manual

Based on the design inputs about structure and material, the process planning can be conducted, including process selection, process parameter definition and fixture design to ensure that the design requirement can be achieved. The subsections will introduce some of the rules and recommendations about process selection, process parameter definition and fixture design respectively. The structure of process planning guidelines for LBW in the aircraft industry is illustrated in Figure E-8.

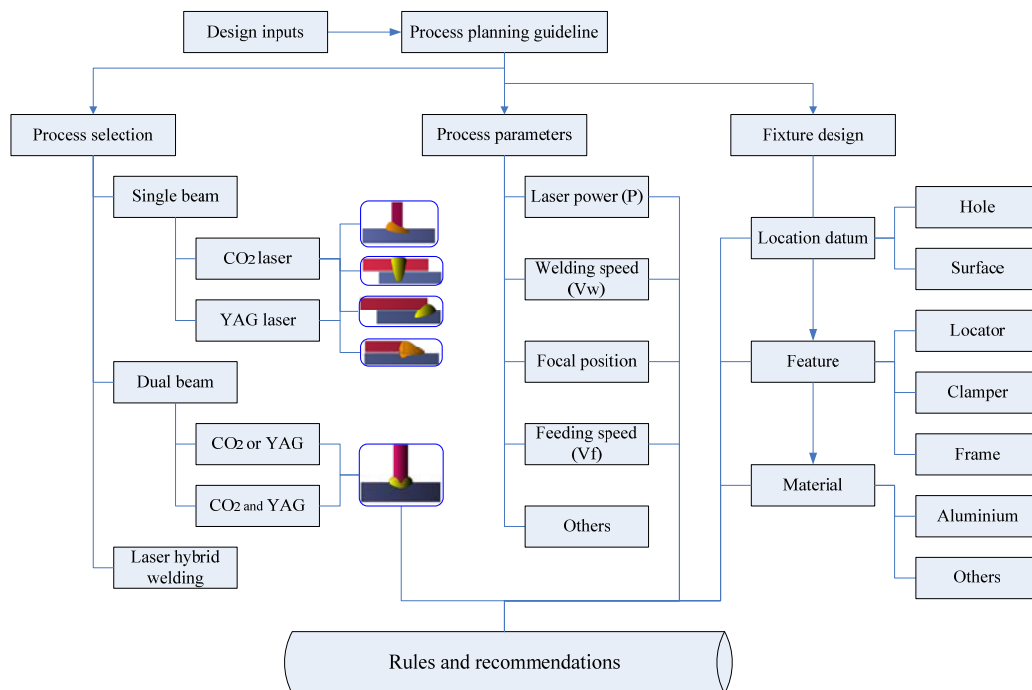
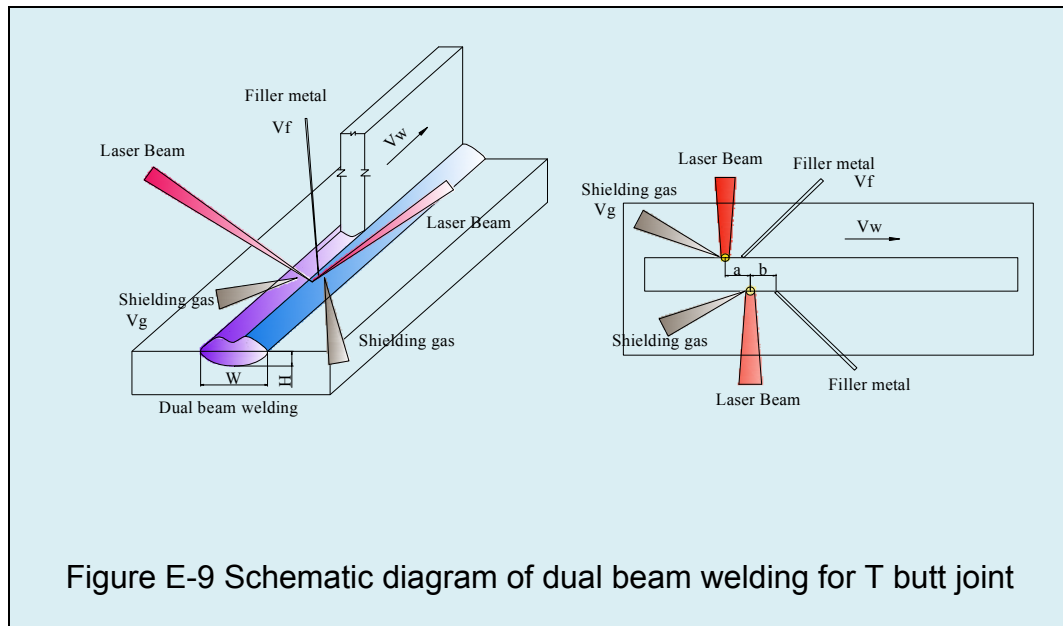


Figure E-8 Structure of process planning guidelines for Laser Beam Welding

### E.7.1. Process selection

✚ “Dual beam welding with two CO<sub>2</sub> lasers is recommended for skin-stringer T butt weld”



The proposed LBW process that has been extensively used for experiments is dual beam welding from both sides of the T butt joint simultaneously, which is schematically illustrated in Figure E-9. Selection of the process is based on the joint type as well as the skin and stringer structure.

Single beam LBW easily causes asymmetric distortion for a T butt joint, because the residual stress formed from shrinkage in this situation is asymmetric. This makes the stringer incline to the side where the laser beam focus onto the joint. Dual beam welding can avoid this situation and gain symmetric angular distortion from symmetric welding, thus it is recommended for a T butt joint. Figure E-10 illustrates the different effect on a T butt joint with single beam and dual beam welding.

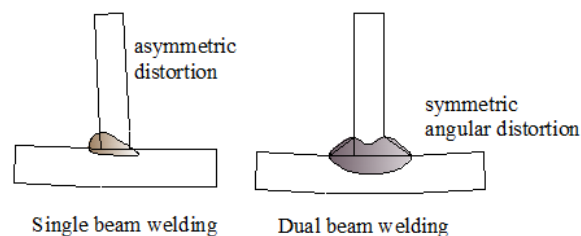


Figure E-10 Schematic diagram of single beam and dual beam welding

Laser-X hybrid welding is not recommended for fuselage panel T butt joint because of the accessibility issue brought by the X process. One possible

exception is a hybrid welding of two different lasers, such as CO<sub>2</sub>-Nd: YAG dual beam welding, but such a process is also asymmetric welding and still needs to be proved by experiments and production. Generally, dual beam welding with two same lasers is recommended for symmetric welding. Also, CO<sub>2</sub> lasers are suggested because of their lower cost comparing with other lasers. The LBW process for stringer-skin T butt joints in Airbus was dual beam welding with two CO<sub>2</sub> Lasers of 3.5 kW beam power.

### E.7.2. Effect of laser power on as-welded geometry

✚ If ( $P \leq P_1$ ) then “the weld pools at two sides of the T butt joint separate, which result in low joint strength”  
 Else if ( $P_1 < P < P_2$  and  $P \uparrow$ ) then “weld width ( $W$ )  $\uparrow$ , weld depth ( $H$ )  $\uparrow$ , weld angle ( $\gamma$ )  $\downarrow$ , angular distortion ( $\phi$ )  $\uparrow$ , deflection ( $\delta$ )  $\uparrow$ ”  
 Else if ( $P \geq P_2$ ) then “the skin is fully penetrated which induces risk of sealing and dropout”  
 Where  $P_1$  is the critical power that makes the weld pools from two sides of the T butt joint join together and  $P_2$  is the critical power that makes fully penetration of skin. These two critical powers are not constant in different conditions.

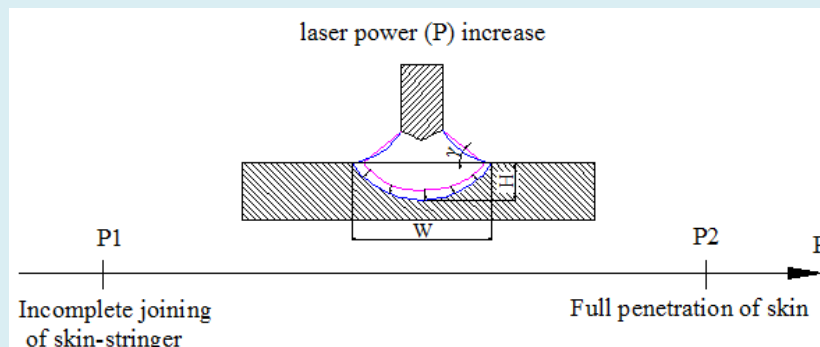


Figure E-11 Effect of laser power to weld profile for T butt joint

Laser power ( $P$ ) is one of the key process parameters of LBW as it relates to the power density ( $I$ ) and linear heat input ( $E'$ ) directly, which will influence the keyhole mode and welding deformation. Actually, the weld width ( $W$ ), weld depth ( $H$ ), deflection ( $\delta$ ) and angular distortion ( $\phi$ ) increase with the laser power, whilst the angle of weld profile ( $\gamma$ ) decreases.

The as-welded geometry of a skin-stringer T butt joint is schematically illustrated in Figure E-12, having five main parameters, namely weld width “W”, weld depth “H” and angle of weld profile “ $\gamma$ ” for weld cross-section, and deflection “ $\delta$ ” and deformation “ $\phi$ ” for angular distortion.

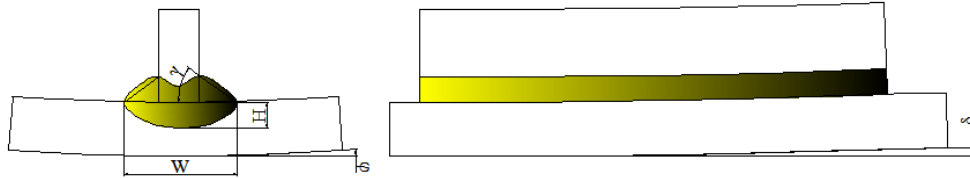


Figure E-12 Representation of as-welded geometry

The power density ( $I$ ) and linear heat input ( $E'$ ) increase with the laser power. Thus, the absorbed energy by the welding area on the workpiece increases, which results in an increase of weld width and depth. The effect of laser power to HAZ in general is illustrated in Figure E-13.

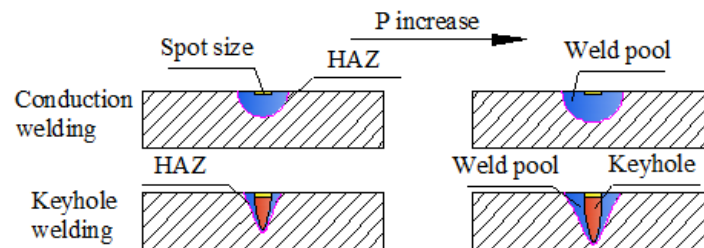


Figure E-13 Effect of laser power on Heat Affected Zone in general

For a T butt joint with filler, the melt of the filler metal accelerates when the laser power increase, so the molten metal has more time to deform under the effect of gravity before solidification. The weld turns to a concave profile and the angle of weld profile decreases. The expanded HAZ increases the residual stress as well as the angular distortion and deflection. Figure E-11 illustrates the change of weld profile when the power decreases.

### E.7.3. Effect of welding speed on as-welded geometry

✚ If ( $V_w \leq V_{w1}$ ) then “skin is likely to be fully penetrated”

Else if ( $V_{w1} < V_w < V_{w2}$  and  $V_w \uparrow$ ) then “weld width ( $W$ ) ↓, weld depth ( $H$ ) ↓, weld angle ( $\gamma$ ) ↑, angular distortion ( $\phi$ ) ↓, deflection ( $\delta$ ) ↓”

Else if ( $V_w \geq V_{w2}$ ) then “undercut is likely to exist because of short of filler metal”

Else if ( $V_w \geq V_{w1}$ ,  $V_f/V_w$  keep constant and  $V_w \uparrow$ ) then “weld width ( $W$ ) ↓, weld depth ( $H$ ) ↓, weld angle ( $\gamma$ ) ↑, angular distortion ( $\phi$ ) ↓, deflection ( $\delta$ ) ↓”

Where  $V_{w1}$  is the critical welding speed that makes full penetration of skin and  $V_{w2}$  is the critical welding speed that results in undercut from shortage of filler metal. These two critical welding speeds are not constant in different conditions.

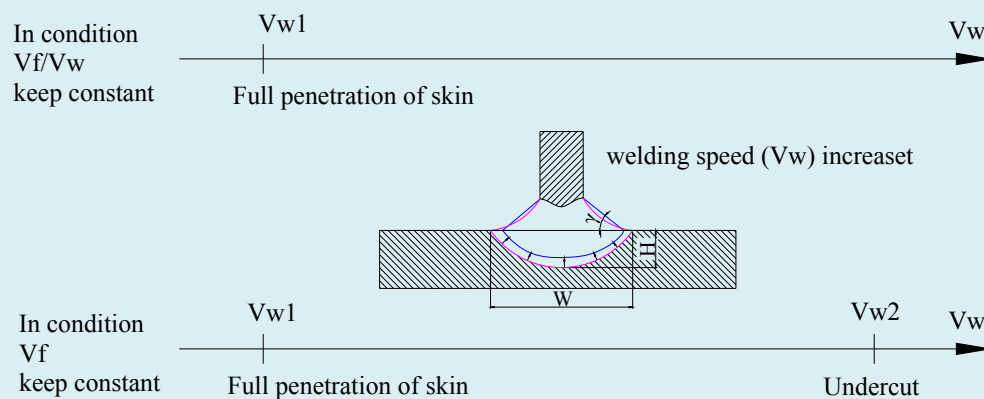


Figure E-14 Effect of welding speed on weld profile for T butt joint

Welding speed ( $V_w$ ) is the speed of relative motion between the laser beam and workpiece which can result from the motion of either the laser beam or workpiece, or both. It is another key process parameter of LBW as it relates to the linear heat input ( $E' = P/V_w$ ) directly. The weld width ( $W$ ), weld depth ( $H$ ), deflection ( $\delta$ ) and angular distortion ( $\phi$ ) all decrease when the  $V_w$  increases, while the angle of weld profile ( $\gamma$ ) increases. Figure E-16 illustrates the effect of welding speed on weld profile for T butt joint.

The linear heat input ( $E'$ ) decreases with the welding speed ( $V_w$ ). Thus, the absorbed energy by the welding area on the workpiece decreases, which causes a reduction of weld depth and weld width. The effect of  $V_w$  to HAZ in general is illustrated in Figure E-15.

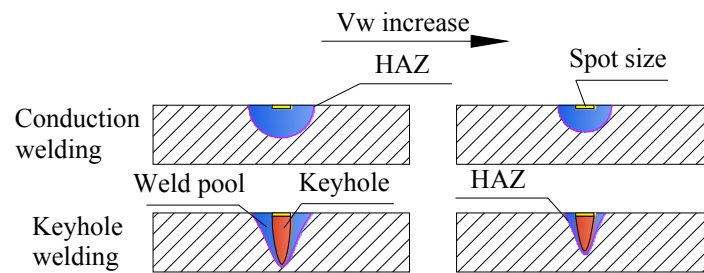


Figure E-15 Effect of welding speed on weld geometry in general

For a T butt weld with filler metal, the melt and solidification both accelerate when the welding speed increases. High speed is preferred by engineers because low speed may cause dropout or undercut from over-vaporization of metal and high residual stress from a large HAZ. However, the increase of  $V_w$  decreases the ratio of  $V_f$  and  $V_w$  ( $V_f/V_w$ ), which means the filler added to the workpiece per unit time decreases. This will also result in undercut. So in industry application, this ratio is usually kept at a relatively constant value to avoid this defect. Figure E-16 illustrates the variety of weld profiles roughly when the  $V_w$  increases.

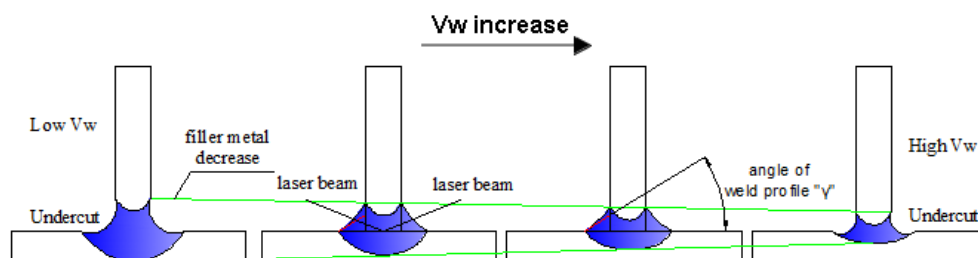


Figure E-16 Different weld profiles at different welding speeds



In case the  $V_w$  is not too low or too high and the ratio  $V_f/V_w$  remains relatively constant, when the  $V_w$  increases, the angle of weld profile will increase as illustrated in Figure E-16. The reduced HAZ caused by high  $V_w$  means less residual stress, and results in a reduction of angular distortion and deflection.

#### E.7.4. Stringer fixture design recommendation

✚ “A stringer guiding system fixed with the working head is recommended to locate and clamp the stringer accurately as well as avoiding influence to the path of the laser beam”

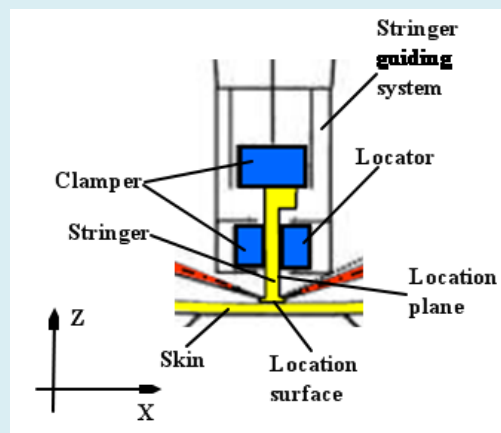


Figure E-17 Schematic diagram of stringer guiding system  
(Rendigs and knower, 2010)

A stringer fixture is an equipment or system to locate the stringer at the required position relative to the skin and to clamp the stringer firmly to the skin to gain good fit-up. A basic and typical location and clamping solution for a stringer is illustrated in Figure E-18. The inside surface of the skin and the side planes A and C of the stringer build the location system of the stringer.

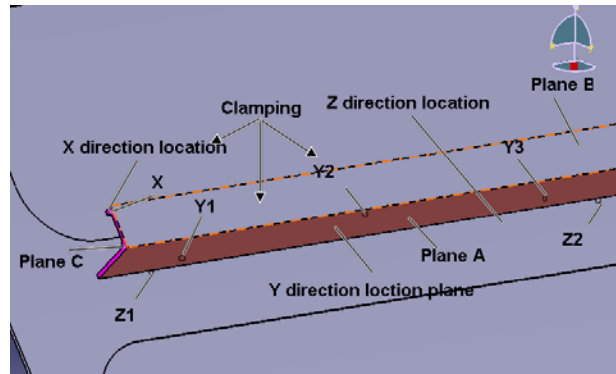


Figure E-18 A basic and typical location and clamping system of the stringer

The stringer is so long that it is actually difficult to locate and clamp it using such a simple system. In fact, the stringer is always located by an over restrained system to ensure each section of the stringer is at the right position because it is crucial to the beam-joint alignment which will influence the weld quality. This was achieved through using more locators and clampers within the traditional solution. However, it is not suitable for LBW as these clampers and locators are likely to stop the laser beam occasionally when the laser beam moves along the joint during the welding procedure. A stringer guiding system fixed to the working head, as shown in Figure E-17, will resolve this issue as the location and clamping system is moving with the laser beam. Thus, this solution is recommended for LBW of the skin-stringer connection.

## E.8. Summary

This handbook has given a brief introduction to the principles of LBW and the related parameters, as well as the advantages, disadvantages and applications of LBW in order to develop an understanding of LBW process in the aircraft industry. After that, the structure design and process planning manual were described, with some rules and recommendations to facilitate the structure and fixture design and the process parameter optimization.

This is just a prototype of the final handbook, because only some rules about the definition of structure, selection of process parameter and fixture design as validated by experts from CU and COMAC, have been described in detail. The structure design and process planning procedure are not included and rules which have not yet been validated have not been discussed in detail.

## **Appendix F    Questions for validation**

### **F.1.   Questions for initial validation:**

- 1) What do you think of the categorization of rules and recommendations?
- 2) Are these rules and recommendations easy to understand?
- 3) Is the rule correct or wrong?

### **F.2.   Questions for further validation:**

- 1) What are the strength of these rules and recommendations?
- 2) What are the weakness of these rules and recommendations?
- 3) Do you think they can also be applied to other industries?